ASET-B: Comparison of Model Predictions with Full-scale Test Data

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BACKGROUND

The proper use of computer fire models requires an understanding of their applicability and limitations, since all computer models are, at least to a certain extent, empirically based. Equations or constants used within computer models are frequently based on curve fits to data from experiments. Typically, the experiments used to develop the correlations were conducted under a limited set of conditions, e.g., compartment sizes, heat release rates or fire growth rates. If the computer model is used for an application that falls outside of the bounds of the experiments used to develop the correlations, uncertainty may be introduced. Additionally, inaccuracies can be introduced in the numerical methods used to solve integral or differential equations, or more simply in math errors that were created during coding of the program.

To facilitate a greater understanding of the limitations of computer fire models by model users, the Society of Fire Protection Engineers has formed a computer fire model evaluation task group. The task group follows the evaluation methodology contained in ASTM ***Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models,*** **E-**1355.[1] The ASTM methodology addresses four areas of evaluation: 1) model definition and evaluation scenarios, 2) verification of theoretical basis and assumptions used in the model, 3) verification of the mathematical and numerical robustness of the model, and 4) quantification of the uncertainty and accuracy of the model predictions.

A subset of the evaluation effort is the evaluation of the predictive capability of the model. ASTM E-1355 identifies three methods that can be used to evaluate the predictive capability of a model: blind calculations, specified calculations, and open calculations. For blind calculations, the modeler is provided with a basic description of the fire scenario to be modeled. This allows for an evaluation of both the predictive capability of the model and the ease of translating scenario characteristics into model inputs. When conducting specified calculations, the modeler is presented with a complete description of model inputs. For open calculations, the modeler is given a complete description of the scenario, and is allowed to select the most appropriate model inputs. For each of these three methods, comparisons of model predictions with standard tests, full scale tests conducted specifically for the evaluation or previously published full-scale test data can be used.

This paper describes an evaluation of the predictive capability of **ASET-B.** "Open calculations" are used for comparisons with previously published full-scale test data.

TEST DESCRIPTIONS

For this evaluation, two sets of previously published full-scale test data were used. The first set of data came from a set of smoke filling experiments conducted in a 5.62 meter × 5.62 meter × 6.15 meter enclosure by Hagglund et al.[2] The second set of data came from tests conducted in an abandoned Nike missile silo with horizontal dimensions of **18.9** meters × 9.1 meters with a ceiling height of 2.35 meters.

6 m^3 enclosure

With the exception of a 0.35 meter wide by 0.25 meter high opening located on a wall at floor level, the room where the fire tests were conducted was closed. The walls and ceiling were constructed of concrete. The fire sources for these experiments were kerosene in square pans that measured 0.25 meters, 0.50 meters or 0.75 meters on a side. Fifteen different experiments were conducted with the pan in either the center of the room, the center of one of the walls, or in a comer. For the fires in the center of the room, the fire source was elevated 0.2 meters, 3.0 meters or **4.5** meters above the floor. For the fires located along a wall or in the comer, the pan elevation was 0.2 meters above the floor level in all of the tests.

During the experiments, mass loss was measured using a load cell, and recordings of the elevation of the smoke layer were made based on video tape data, visual observations and smoke density measurements. Smoke layer temperatures were also recorded using five trees of bare wire thermocouples located in the center and in each comer of the room with thermocouples spaced at 0.50, 1.00, 1.50, **2.00, 2.50,** 3.00, **3.50, 4.00,** 4.50, 5.00, 5.50 and 6.05 meters above floor level. Smoke density measurements were also made at various locations.

A listing of the test conditions can be found in table 1.

Table 1 – Experimental Conditions

Test No.	Pan Size (m)	Pan Location	Pan Elevation (m)
1	0.50 × 0.50	Center	0.20
2	0.50 × 0.50	Center	0.20
3	0.50 × 0.50	Center	0.20
4	0.25 × 0.25	Center	0.20
5	0.25 × 0.25	Center	0.20
6	0.25 × 0.25	Center	0.20
7	0.75 × 0.75	Center	0.20
8	0.50 × 0.50	Wall	0.20
9	0.50 × 0.50	Corner	0.20
10	0.50 × 0.50	Center	3.0
11	0.50 × 0.50	Center	4.5
12	0.50 × 0.50	Wall	0.20
13	0.75 × 0.75	Wall	0.20
14	0.50 × 0.50	Corner	0.20
15	0.75 × 0.75		

The heat of combustion for kerosene was reported as 30 MJ/kg, which was determined using oxygen consumption calorimetry.

Tests #2, 3, 5, ***6,*** 7, 9, 12, 13 and 15 were selected for comparison with model predictions. The temperature data from the thermocouples located 5.50, 4.00 and 1.00 meters above the floor were used for comparisons with ASET-B predictions.

Nike Silo

The Nike silo was a closed, but not sealed, rectangular room. The compartment was constructed of concrete block walls and a 12 mm thick gypsum board ceiling. The area of the ceiling directly above the fire was covered with 12 mm thick calcium silicate boards.

The fire source was a gaseous propane diffusion flame. The burner was an open top cylinder, 0.6 m in diameter and 0.1 m in height, placed directly on the floor. The burner assembly was filled with pea gravel and covered with expanded metal. Heat release rates were calculated based on fuel flow rates. Experiments were run at heat release rates of 28 kW, 56 kW, 112 kW, 168 kW, 224 kW, 280 kW, 336 kW, 392 kW, 448 kW, and 504 kW. More than one replicate test was conducted at each heat release rate; the results fiom tests with the same heat release rates were grouped and analyzed together.

Thermocouple trees were placed at locations 1.5, 3.0, 4.6 and 6.1 meters from the center of the burner. Each of the trees contained thermocouples located at ceiling level and 25, 76, 150, 300, 610, 910 and 1200 mm below ceiling level. Additionally, the thermocouple trees located 1.5 and 6.1 meters from the burner centerline also had an additional thermocouple located 1500 mm below the ceiling.

Data of the layer elevation as a function of time were not available. Therefore, the elevation of the smoke layer was estimated using Cooper's "*N%* rule."[3] The "*N%* rule" first requires calculation of a reference upper layer temperature change based on the maximum temperature change among the thermocouples located at the highest elevation. This can be stated as follows:[4]

$$\Delta T_{ref}(t) = \max\left[T(z_{top},t)\right] - T_{amb}(z_{top})$$

Where $\Delta T_{ref}(t)$ = reference upper layer temperature at time t (°C)

$T(z_{top},t)$ = temperature at top most thermocouple at time t (°C)

z_{top} = the top most thermocouple

$T_{amb}(z_{top})$ = ambient temperature at top most thermocouple at $t = 0$ ("C)

When using the "*N%* rule", z_{top} was taken as the thermocouples located 25 mm below the ceiling.

The "*N%* rule" then states that the interface can be determined to pass elevation $z_i(t)$ at the time t when z_i first satisfies

$$T(z_i,t) - T_{amb}(z_i) = \frac{N\Delta T_{ref}(t)}{100}$$

Where $T(z_i,t)$ = temperature of thermocouple at elevation z_i at time t (°C)

$T_{amb}(z_i)$ = ambient temperature of thermocouple at elevation z_i at time $t = 0$ (°C)

Cooper suggests using a value of $N = 10$.

The "*N%* rule" was implemented as an IF statement in a spreadsheet that contained thermocouple data as a function of time. Determinations as to whether the smoke layer interface height had descended to a given thermocouple elevation were made by visually checking spreadsheets to determine when the columns containing the IF statements changed from "FALSE to "TRUE."

MODELING APPROACH

ASET-B requires the following input:

- Title of run
- Heat loss Fraction
- Height of base of fire
- Room ceiling height
- Floor area
- Maximum run time

The input data was developed as follows (note that **SI** values were converted to imperial since **ASET-B** requires imperial values):

***6* m^3 Enclosure**

The input variables related to dimensions were input based on the physical dimensions of the compartment. For the 6 m^3 enclosure, there variables were as follows:

- Height of base of fire = 0.655 ft.
- Room ceiling height = 20.2 ft.
- Floor area = 338.6 ft^2.
- Maximum run time – set to the length of the test.

The heat release rate was determined by multiplying the measured mass burning rate by the net heat of combustion of kerosene. For the scenarios where the fire was located in the center of the room (test #2, **3,** 5, ***6*** & **7),** the peak burning rate during the scenario was used as a steady state heat release rate input into ASET-B. This tended to overstate the heat release rate during the first 30-60 seconds, as the measured mass loss rate ramped up during this time. Because the tests where the fire was located along a wall or in a corner (tests #9, 12, 13 & 15) typically took longer to reach steady state, the calculated heat release rate during the growth stage was input at 15 second intervals until a maximum rate was achieved, and the maximum heat release rate was used as input for the remainder of the test duration. The heat loss fiaction was varied; for each test **ASET** was run using values of 0.6, 0.7, 0.8 and 0.9.

For tests where the fire was located along a wall, the burning rates determined for the experiments and the floor area were multiplied by a factor **of** two prior to input into ASET-B to account for the reduced entrainment into the fire plume. Similarly, for fires in a corner, the burning rates and floor areas were multiplied buy a factor of four prior to input into ASET-B.

Nike Silo

For the Nike silo data, the variables were input as follows:

- Height of base of fire = 0.3275 ft.
- Room ceiling height = 7.7 ft.
- Floor area = 1844.6 ft^2.
- Maximum run time – set to the length of the test.

The heat release rate was input in accordance with the test specifications. Again, the heat loss fraction was varied; for each test ASET was run using values of 0.6, 0.7, 0.8 and 0.9.

COMPARISON OF MODEL PREDICTIONS WITH DATA

All modeling results were output to text files. Model predictions of the smoke layer elevation and temperature as a function of time were then compared to the data from the 6 m^3 enclosure and the Nike Silo by plotting them on graphs with ASET-B predictions. In each case, predictions for smoke layer temperatures or smoke layer elevations for heat loss fractions (X_l) of 0.6, 0.7, 0.8 and 0.9 are plotted on a single graph along with the applicable test data. It should be noted that the heat loss fraction is expressed as X_l on the graphs, and λ_c in the ASET-B documentation.

While developing the comparisons of predicted and measured smoke layer temperatures, smoke layer temperatures were sampled from the data at discrete time intervals (e.g., every 60 or 100 seconds.) It was observed in all tests that the smoke layer was not a uniform temperature, as assumed by **ASET.** In the comparisons with the Nike silo data, high, low and the average of the high and low thermocouple temperature readings were plotted at 100 second intervals with ASET-B predictions. The 6 m^3 enclosure temperature data is plotted at 60 second time intervals for thermocouple elevations of 1.00 m, 4.00 m and 5.50 m.

In the comparison graphs of predicted and observed smoke layer elevations in the Nike silos, the ASET-B predictions appear as a step function. This is because given the size of the space in comparison to the heat release rates of the fires, the smoke layer descended slowly. Since ASET-B only provides output to the nearest tenth of a meter, several sequential time steps typically had the same predicted smoke layer elevation. Since the fires in the 6 m^3 enclosure were larger with respect to the enclosure size, this does not occur with the ASET-B predictions of the smoke layer elevation.

The ASET-B prediction of smoke layer temperature in the Nike silo with 336 kW fire and a heat loss fraction of 0.9 predicts that the smoke layer temperature decreases at approximately t = 125 seconds. Given the input into **ASET-B,** this is a non-physical phenomena, a possibly reflects numerical instabilities within ASET-B. **ASET-B** failed to converge for predictions of fire effects in the 6 m^3 enclosure test when heat loss fractions of 0.6 and 0.7 were input.

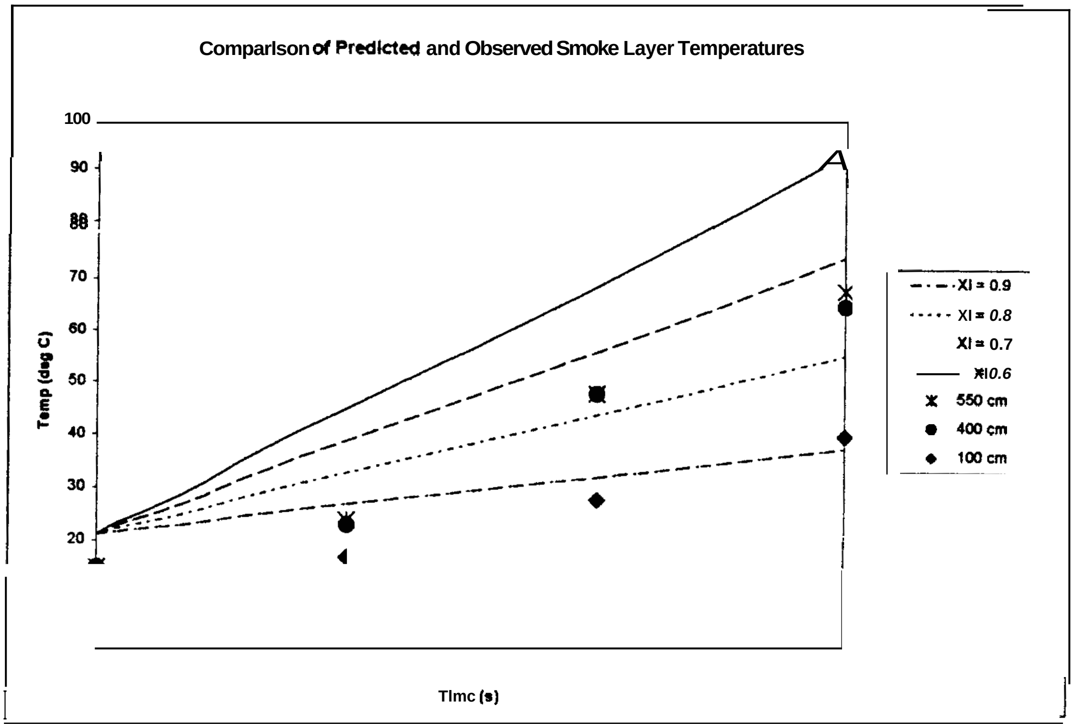
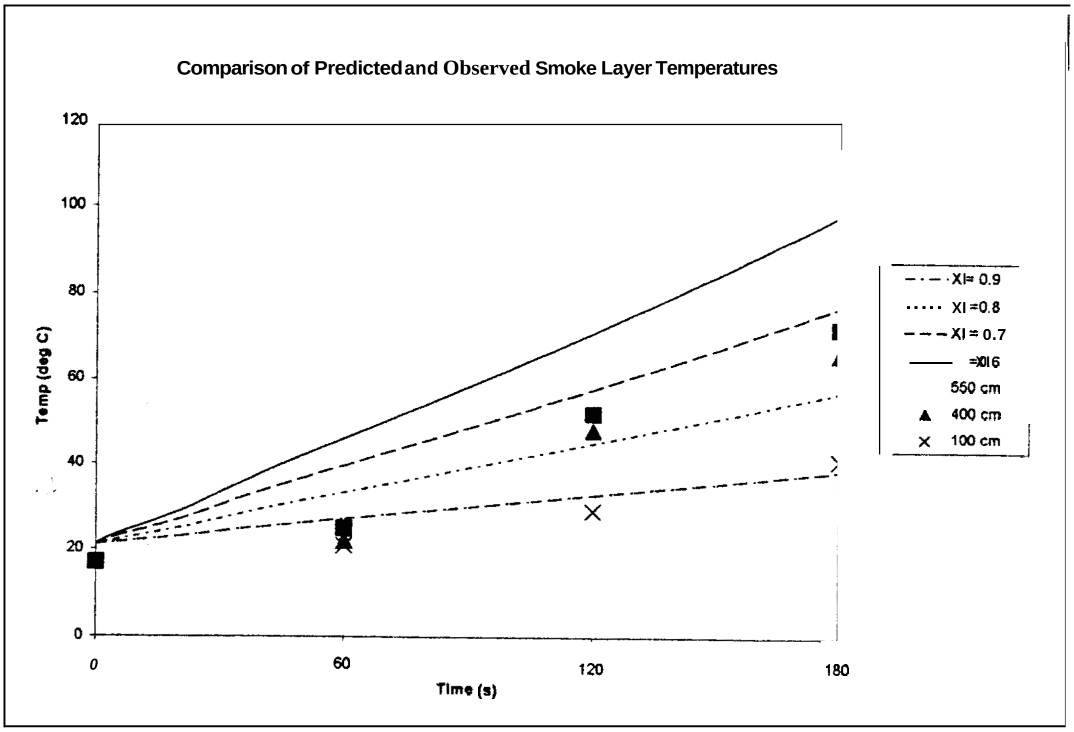


Figure 1 Comparison of Predicted and Observed Smoke Layer Temperatures – 6m^3 Enclosure Test #2



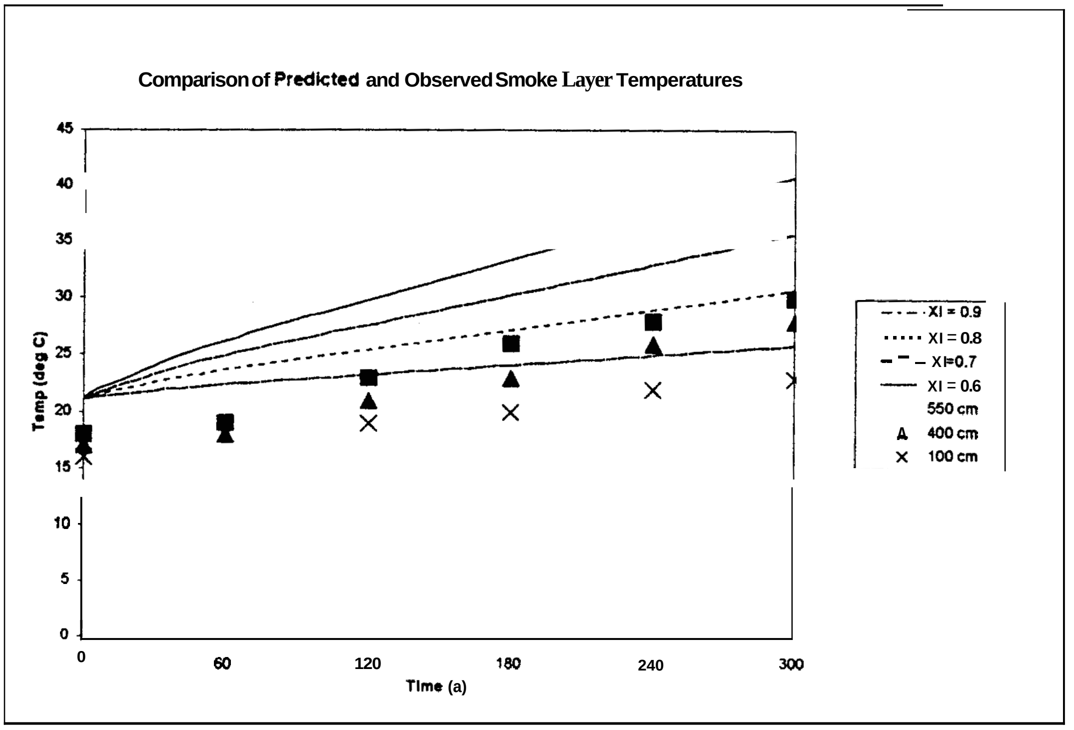


Figure 3 Comparison of Predicted and Observed Smoke Layer Temperatures – 6m³

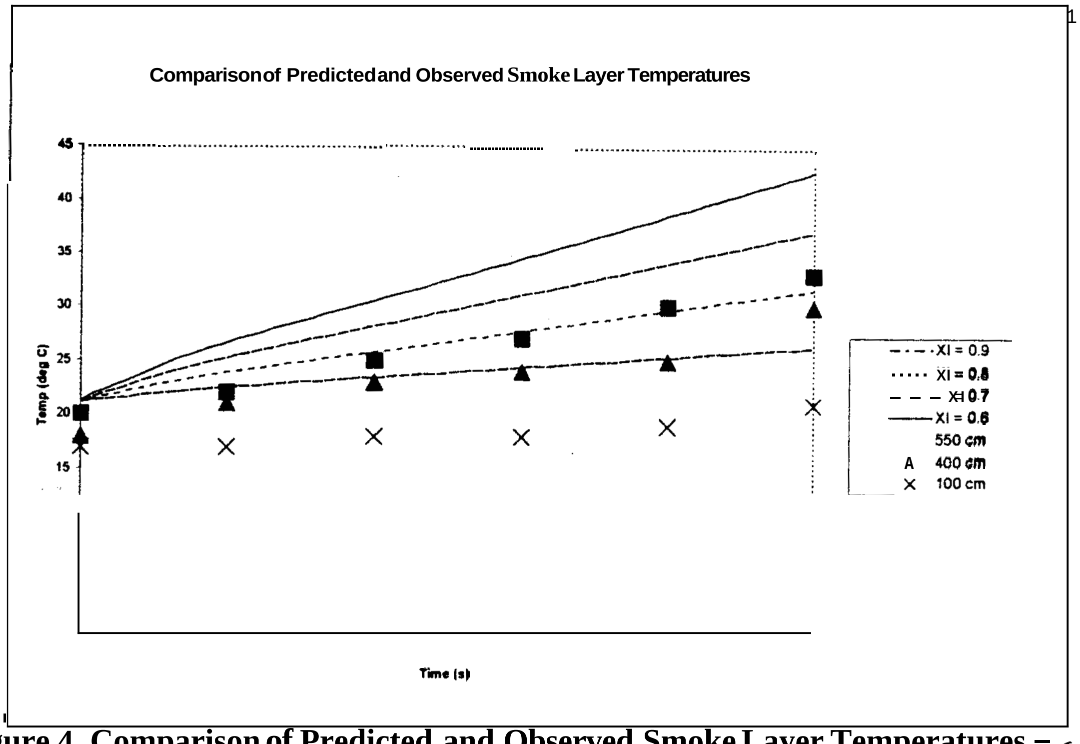


Figure 4 Comparison of Predicted and Observed Smoke Layer Temperatures – 6m³

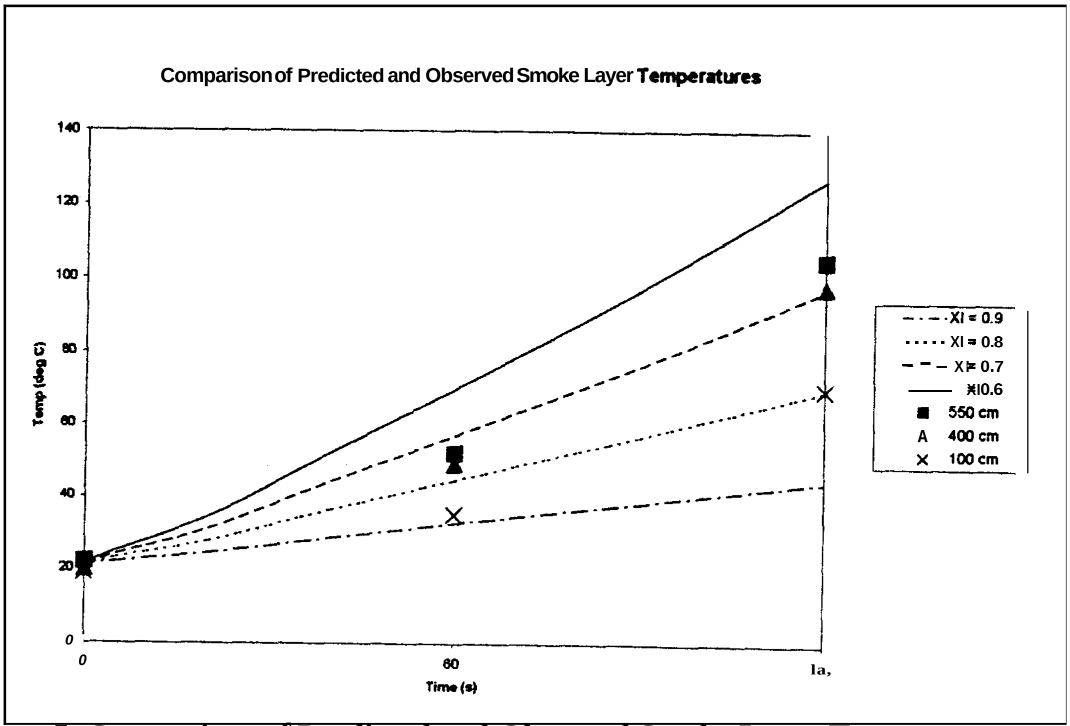
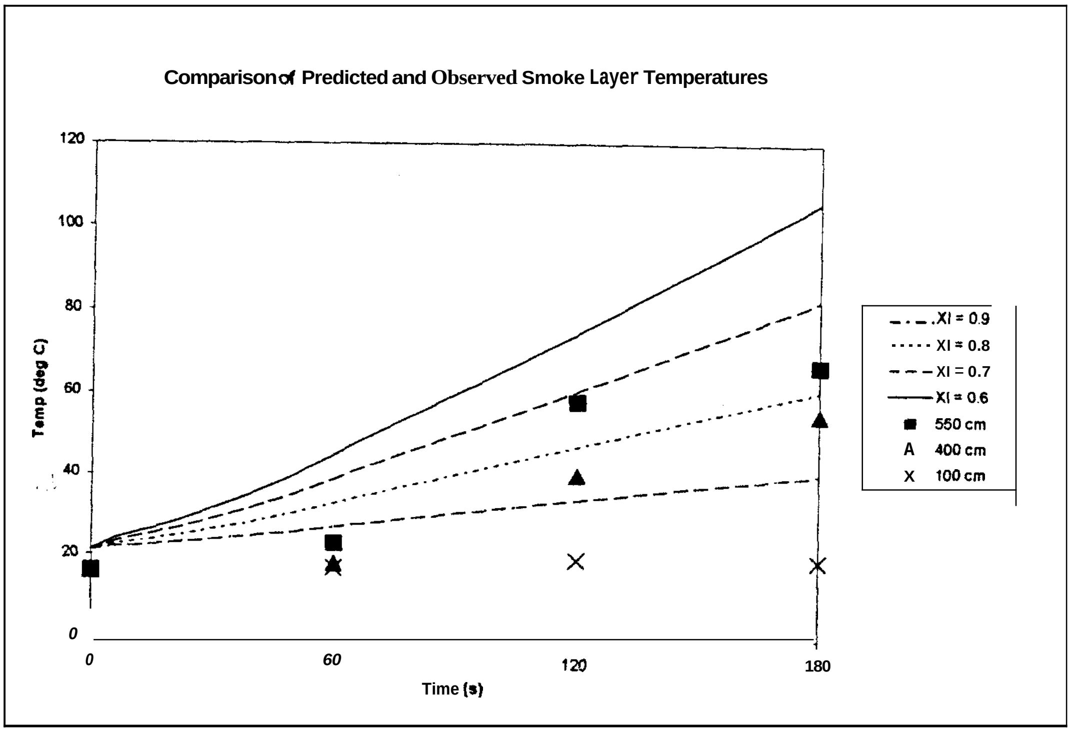


Figure 5 Comparison of Predicted and Observed Smoke Layer Temperatures – 6m[3] Enclosure Test #7



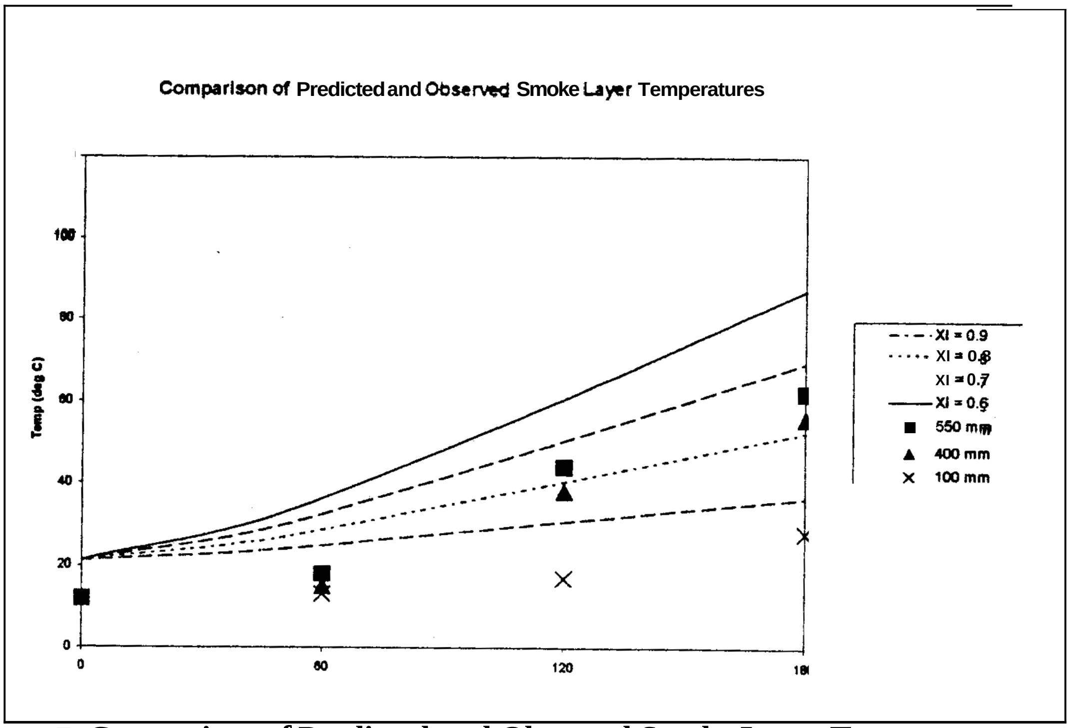


Figure 7 Comparison of Predicted and Observed Smoke Layer Temperatures – $6m^3$

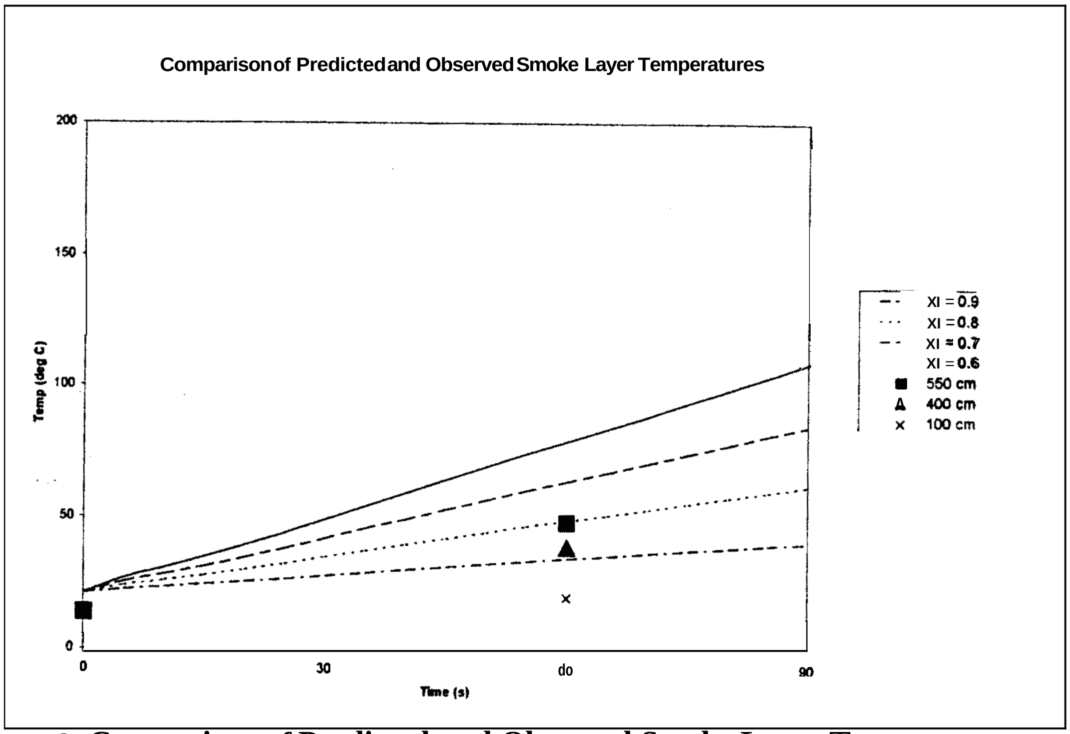


Figure 8 Comparison of Predicted and Observed Smoke Layer Temperatures – $6m^3$ Enclosure Test #13

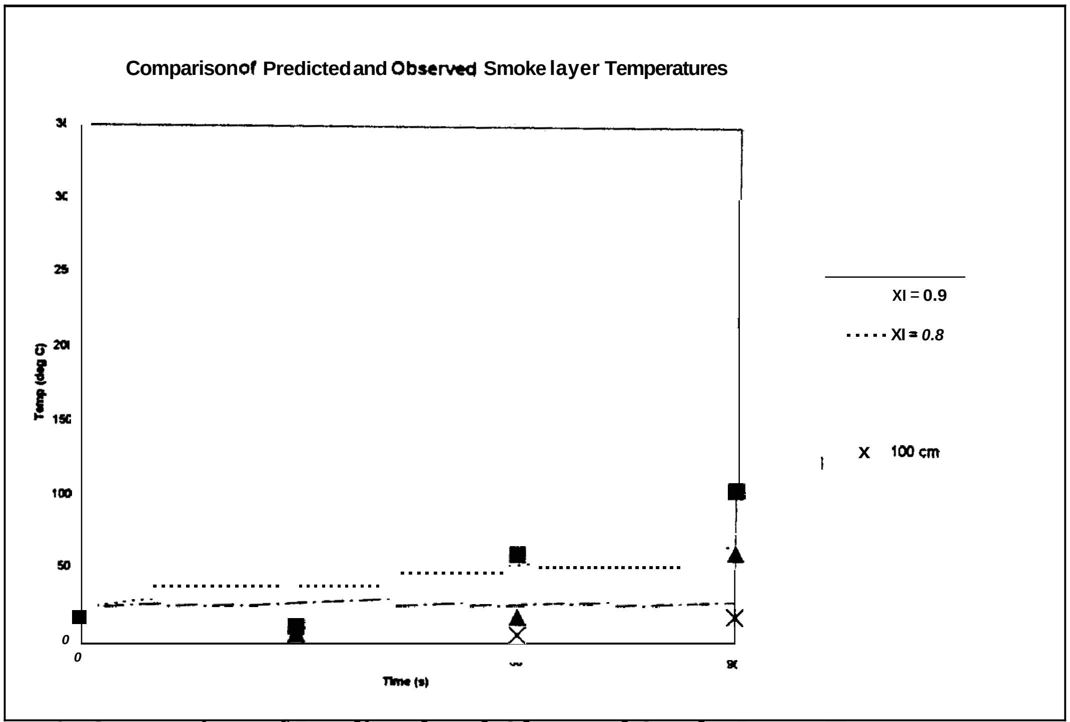
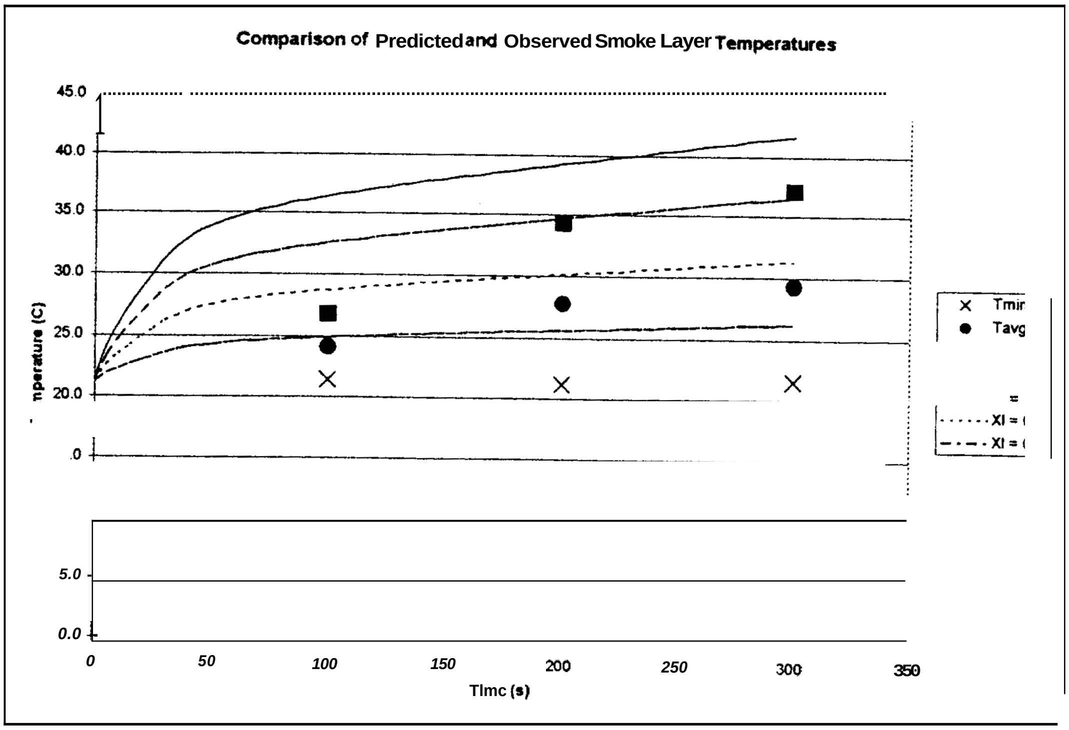


Figure 9 Comparison of Predicted and Observed Smoke Layer Temperatures – 6m^3



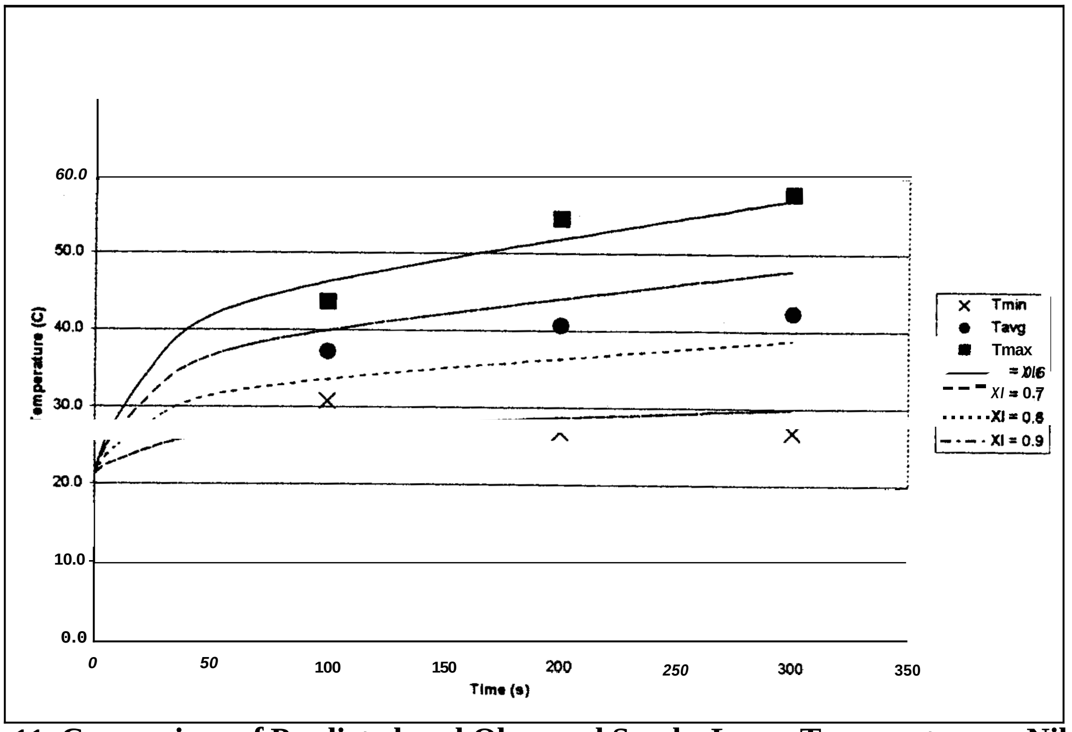


Figure 11 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo

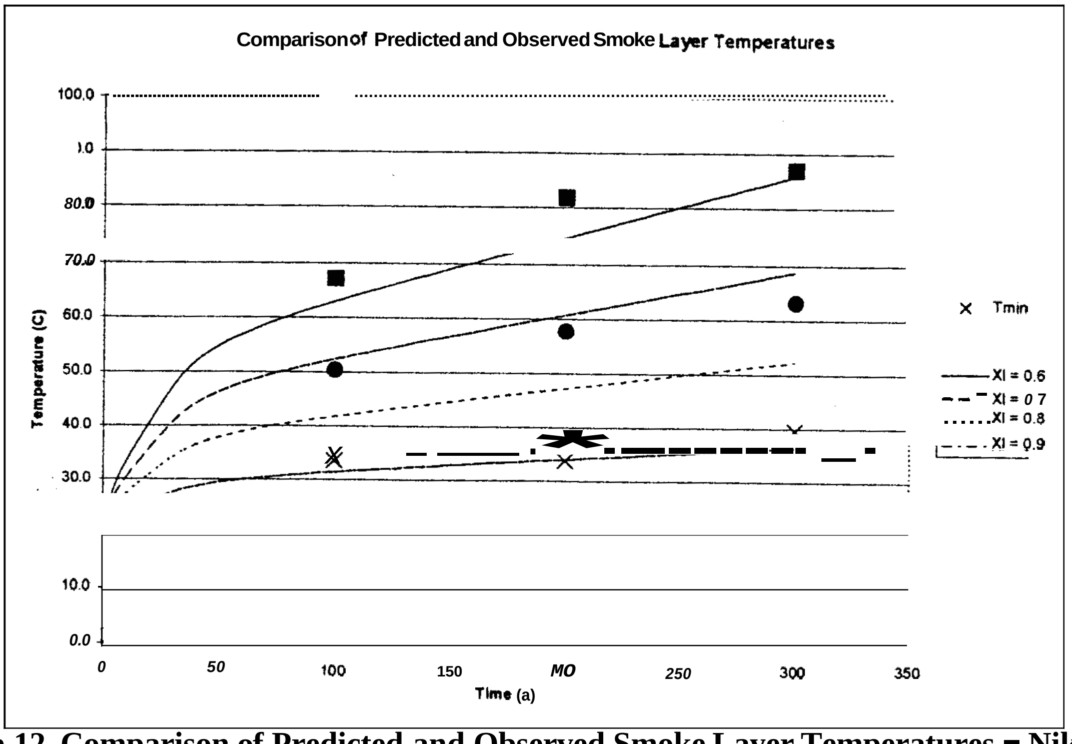


Figure 12 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo

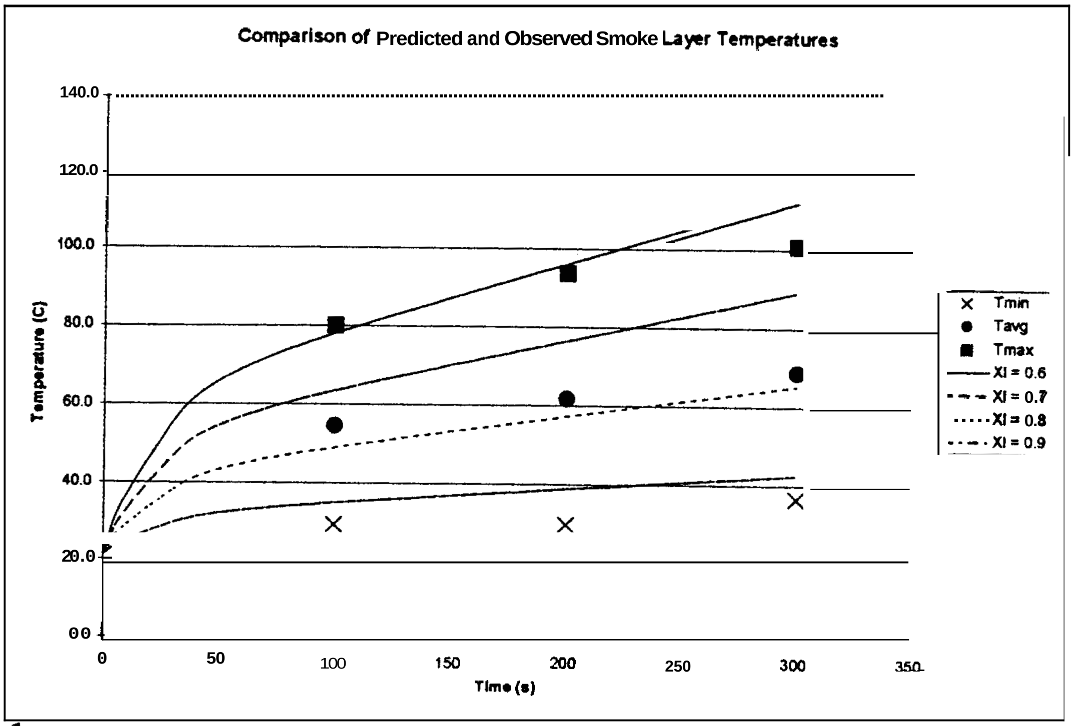


Figure 1

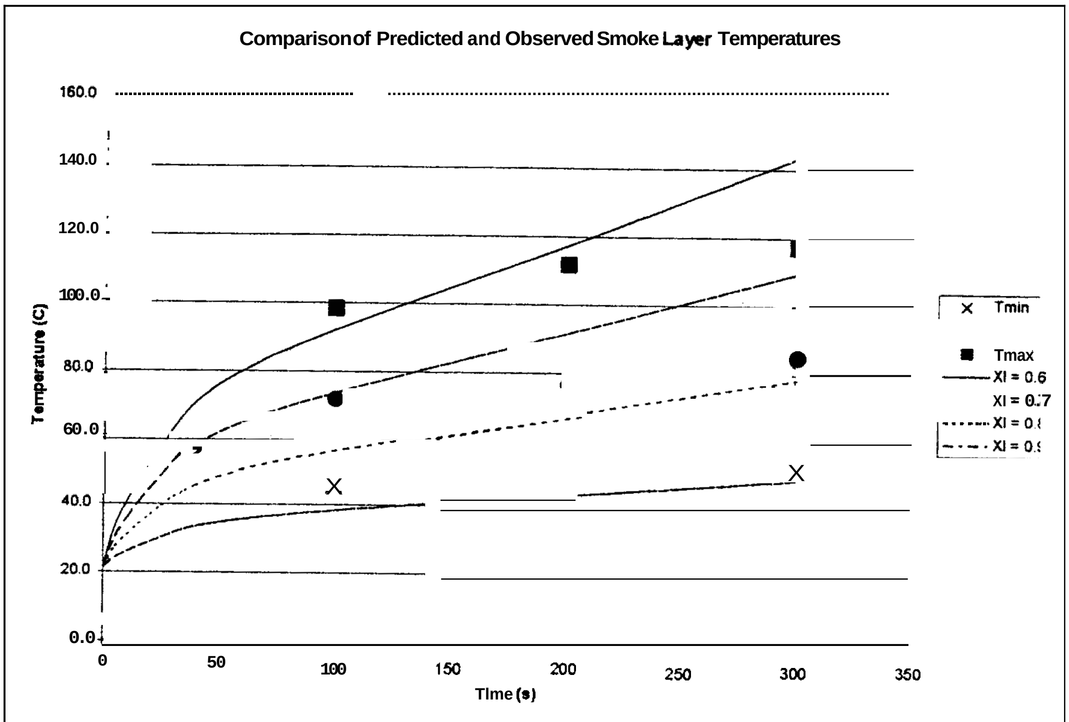


Figure 14 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo with Heat Release Rate = 224 kW

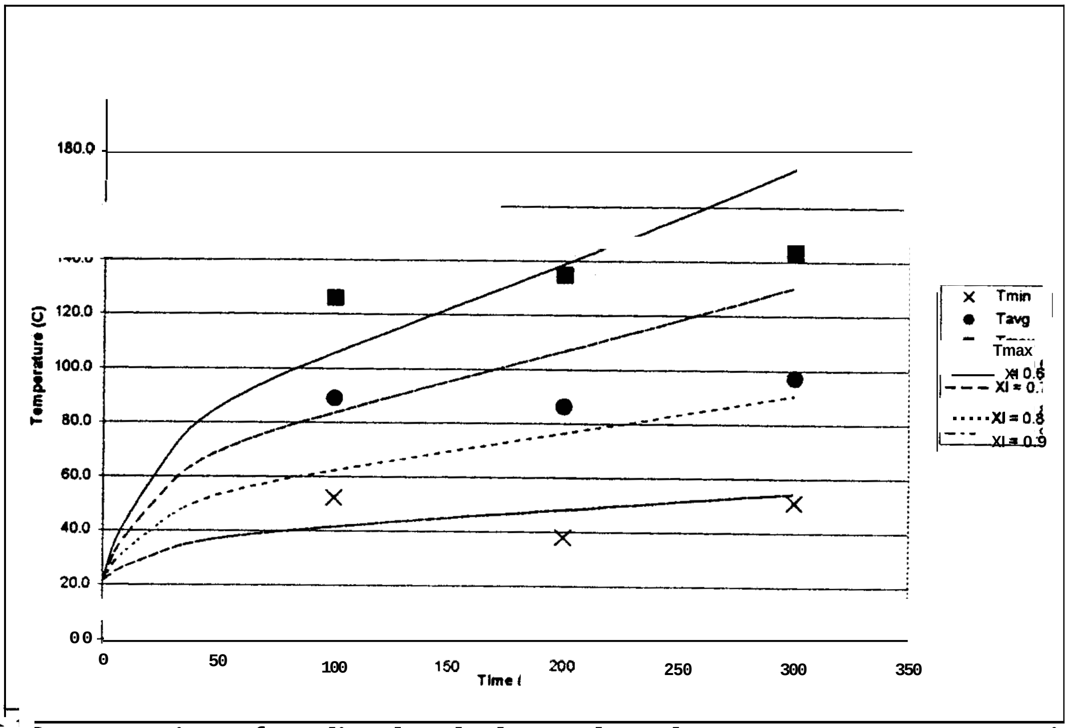


Figure 15 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo

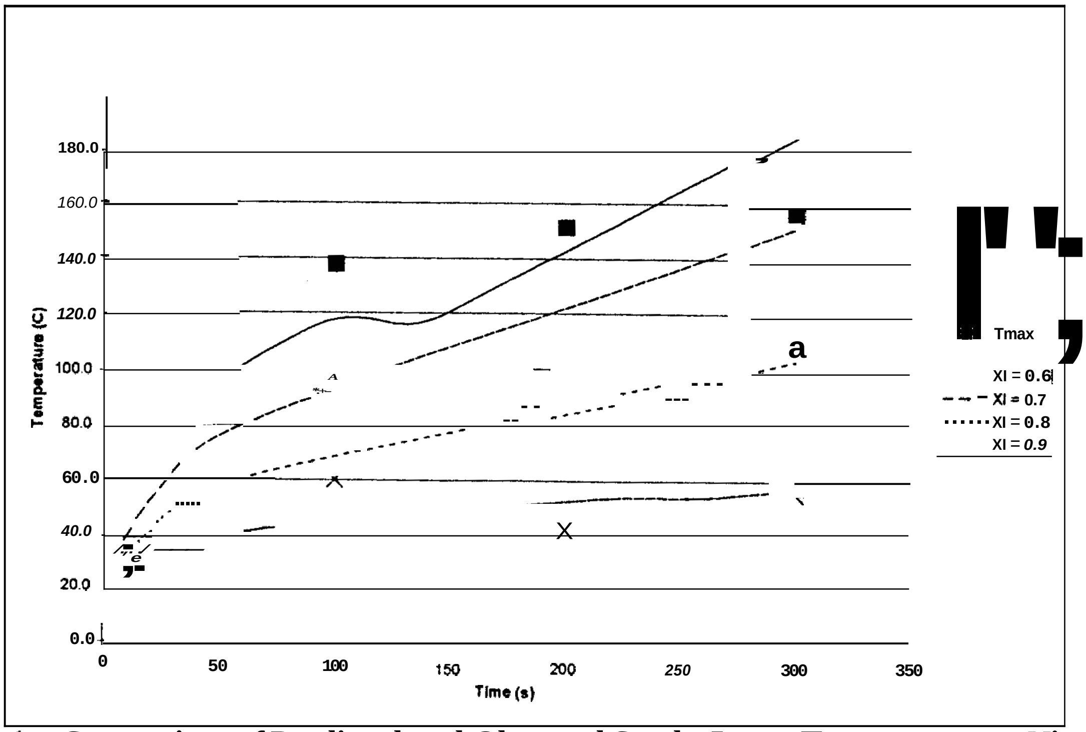


Figure 16 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo with Heat Release Rate = 336 kW

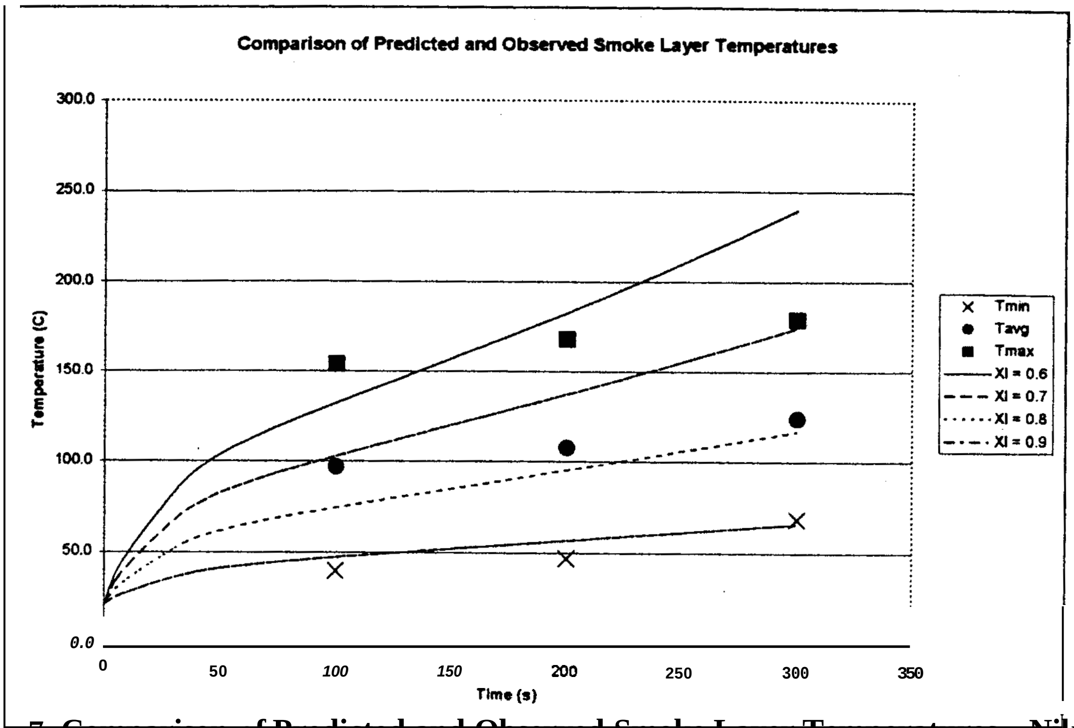


Figure 17 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo with Heat Release Rate = 392 kW

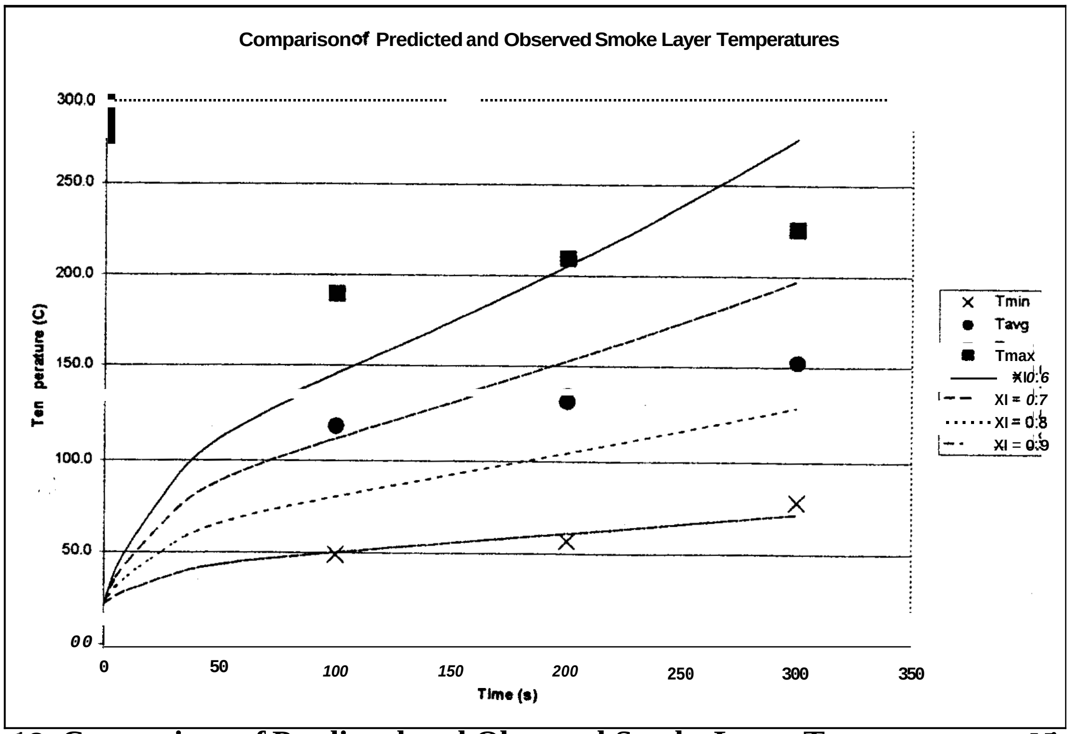


Figure 18 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo with Heat Release Rate = 448 kW

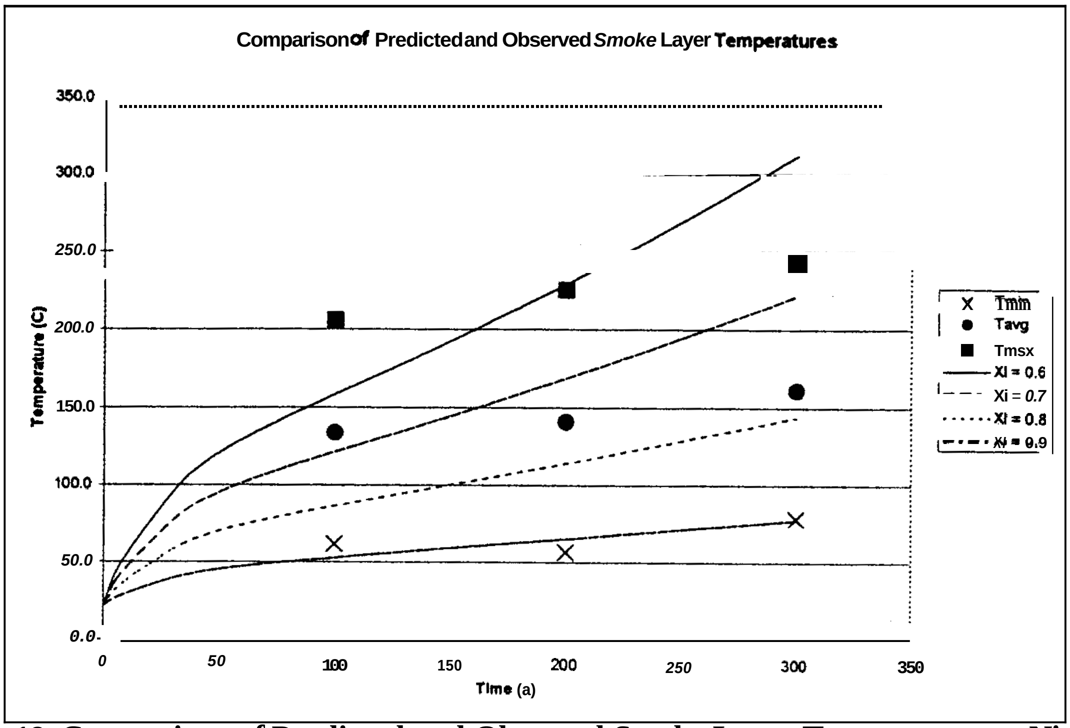
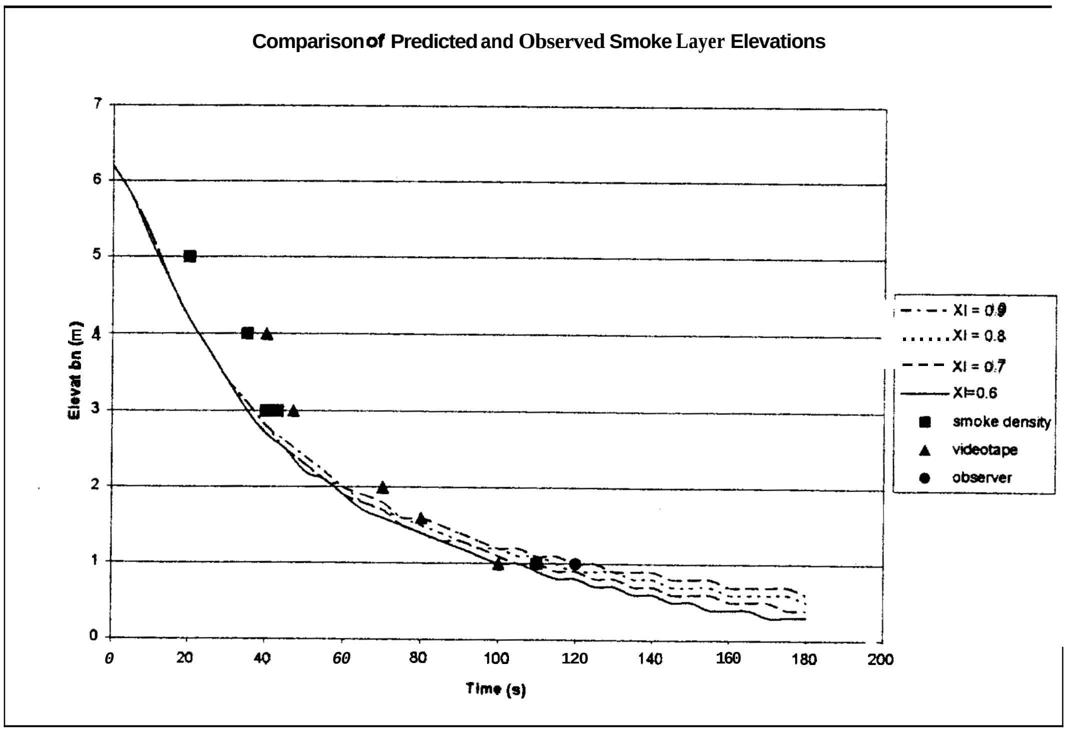


Figure 19 Comparison of Predicted and Observed Smoke Layer Temperatures – Nike Silo with Heat Release Rate = 504 kW



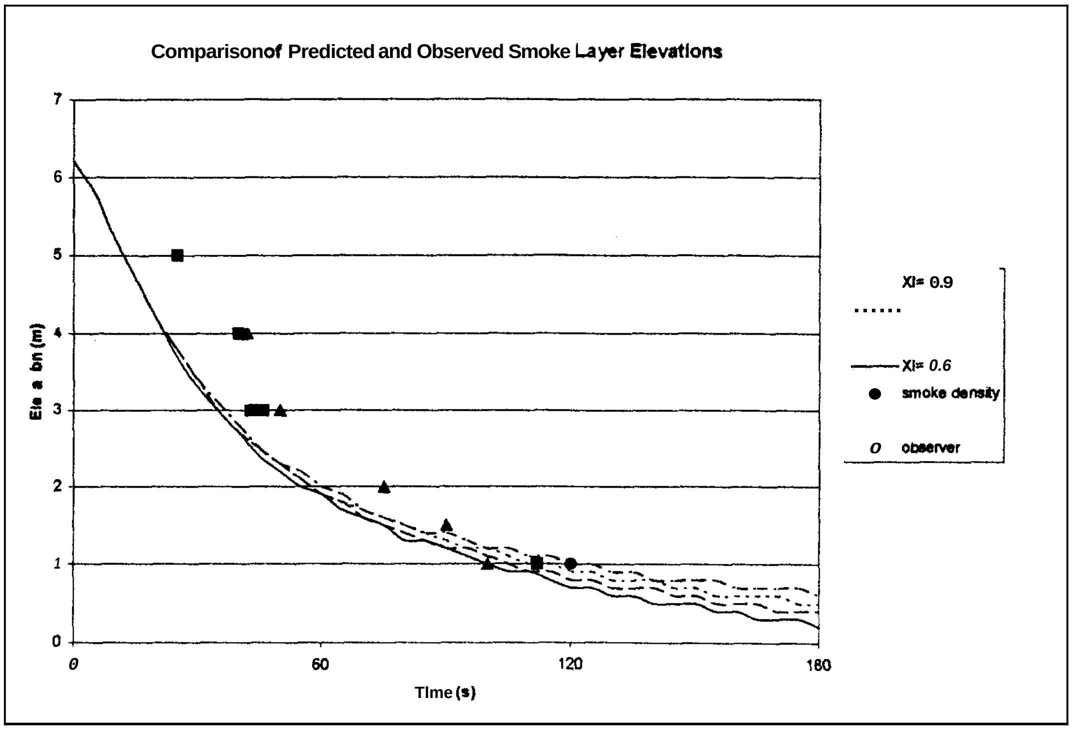
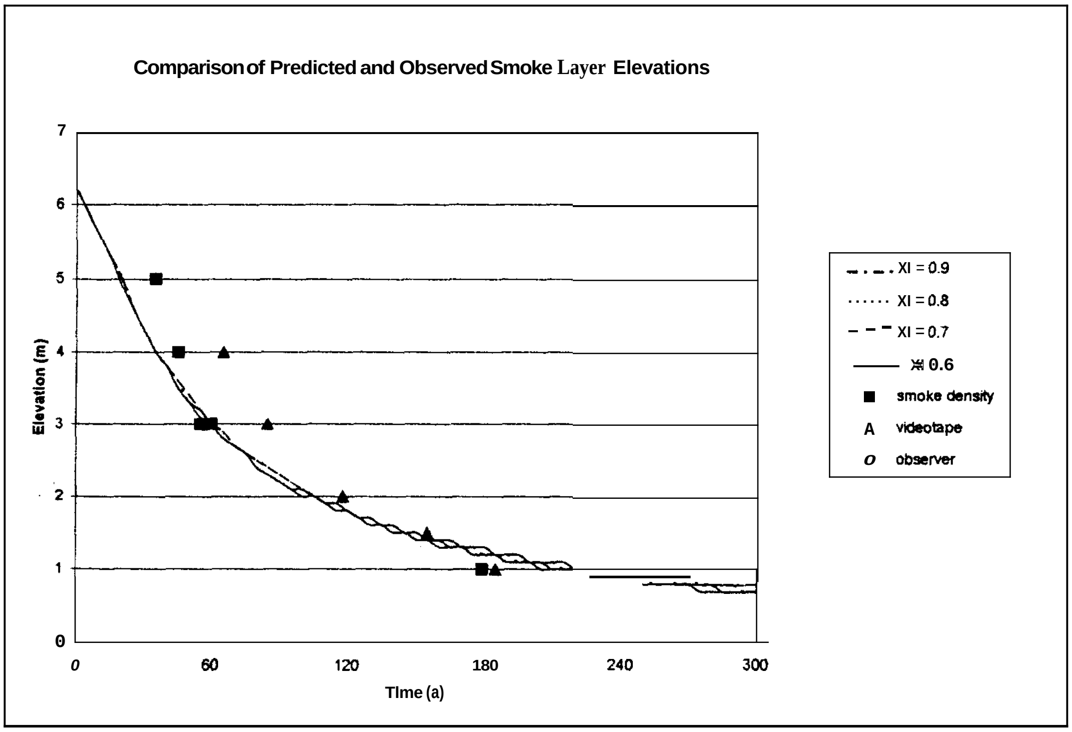


Figure 21 Comparison of Predicted and Observed Smoke Layer Elevations – 6 m³
Enclosure Test #3



Enclosure Test #5

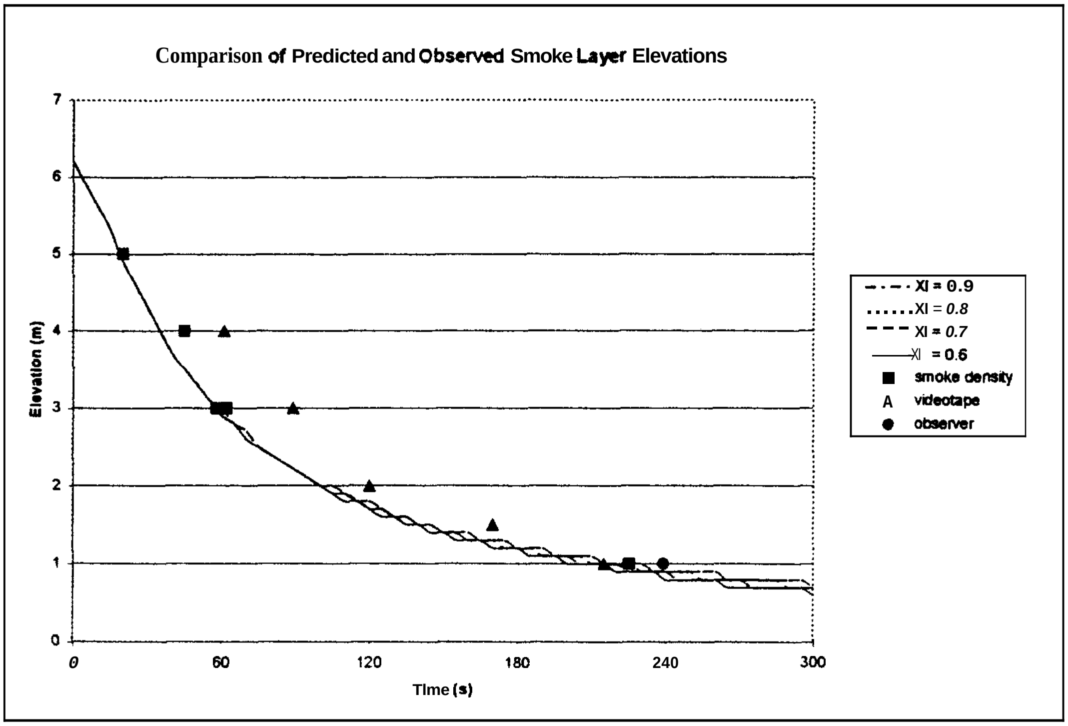


Figure 23 Comparison of Predicted and Observed Smoke Layer Elevations – $6m^3$ Enclosure Test #6

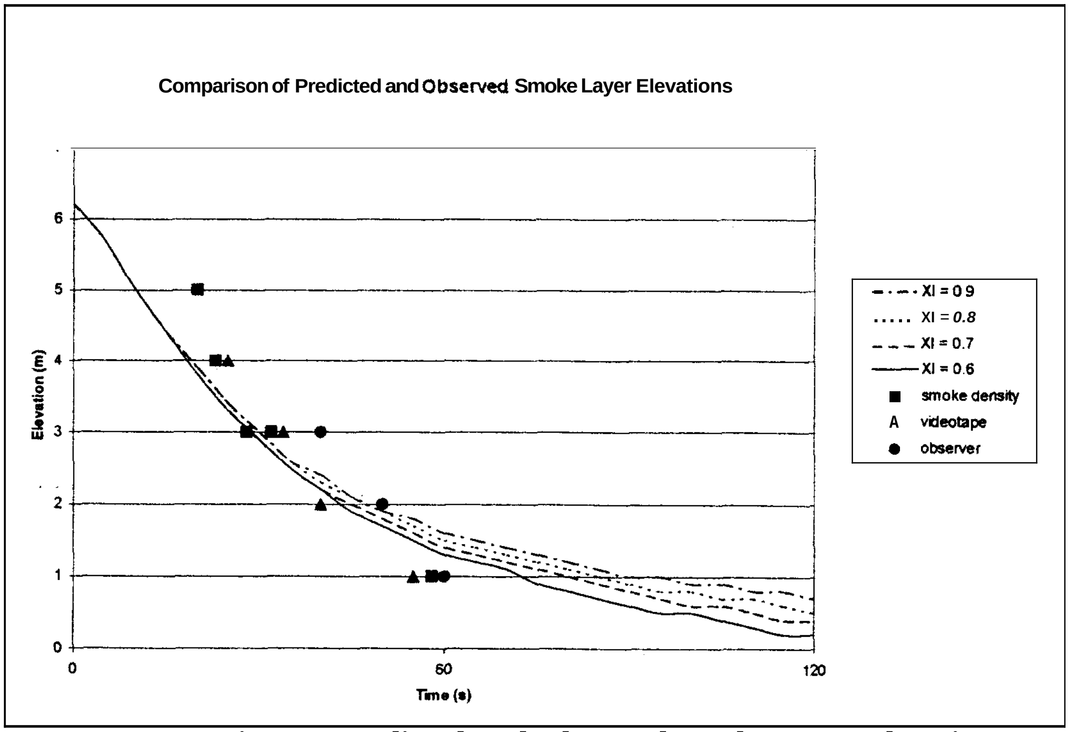


Figure 24 Comparison of Predicted and Observed Smoke Layer Elevations – $6m^3$ Enclosure Test #7

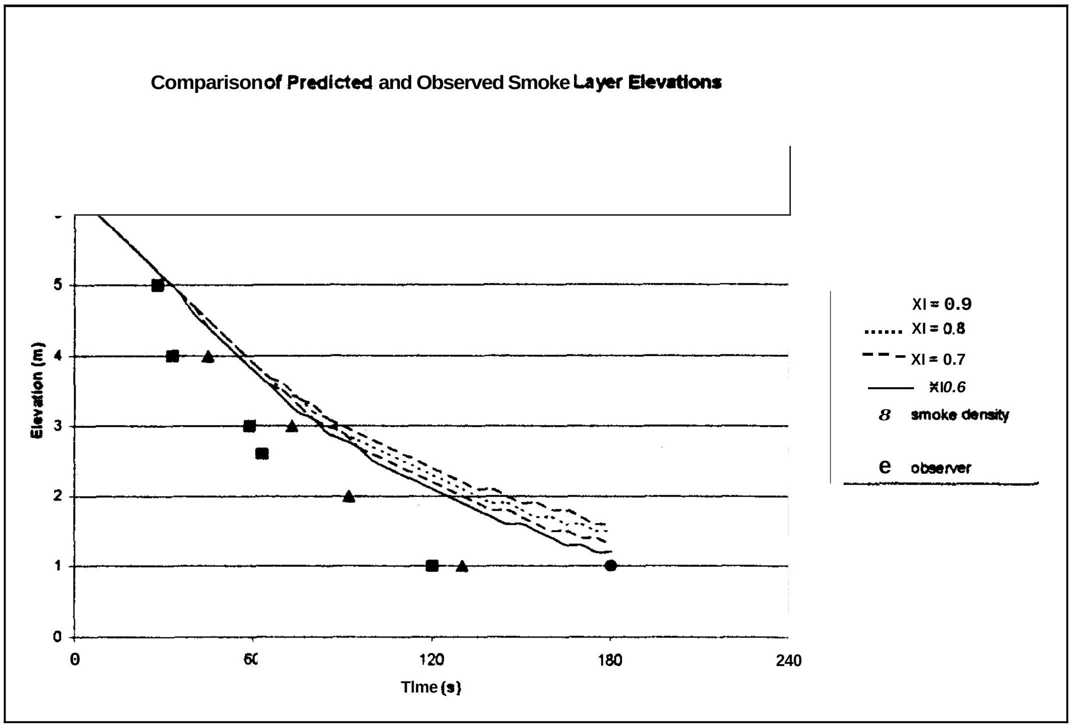


Figure 25 Comparison of Predicted and Observed Smoke Layer Elevations – 6m^3 Enclosure Test #9

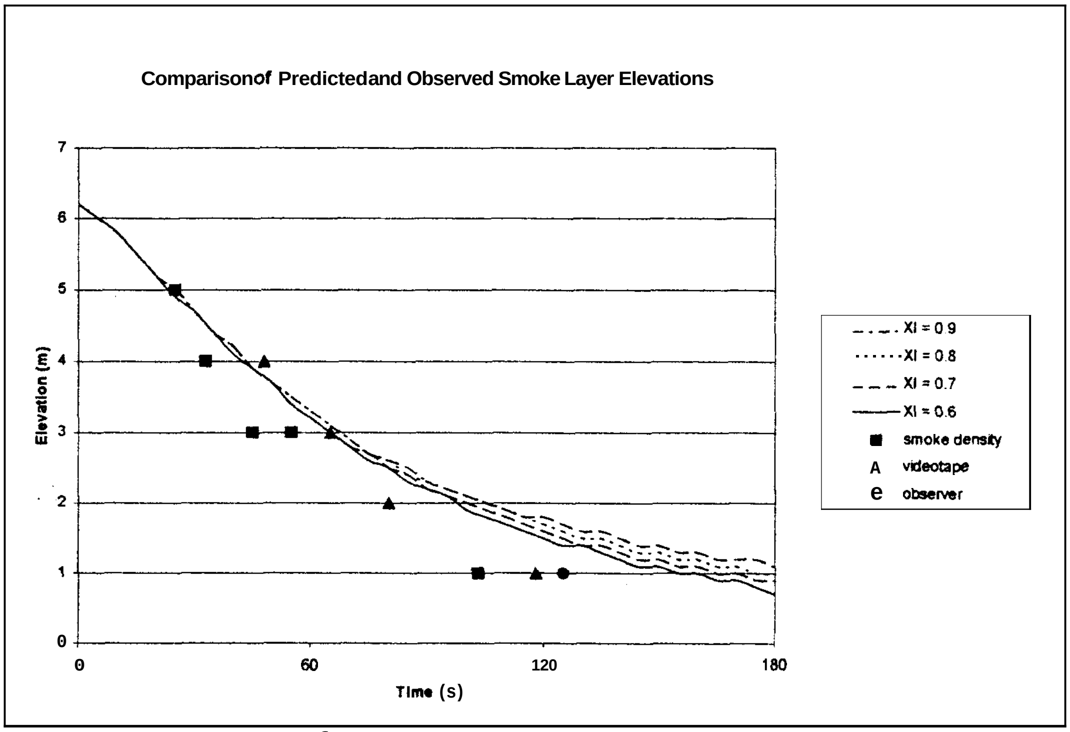


Figure 26 Comparison of Predicted and Observed Smoke Layer Elevations – 6m^3 Enclosure Test #12

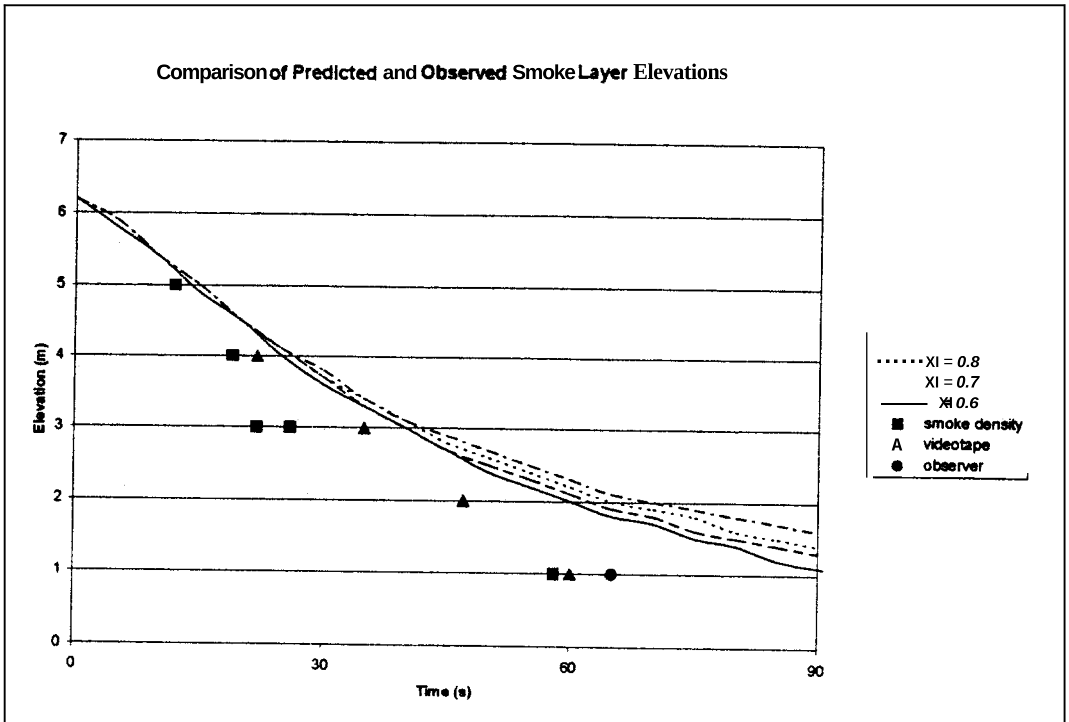


Figure 27 Comparison of Predicted and Observed Smoke Layer Elevations – 6m³

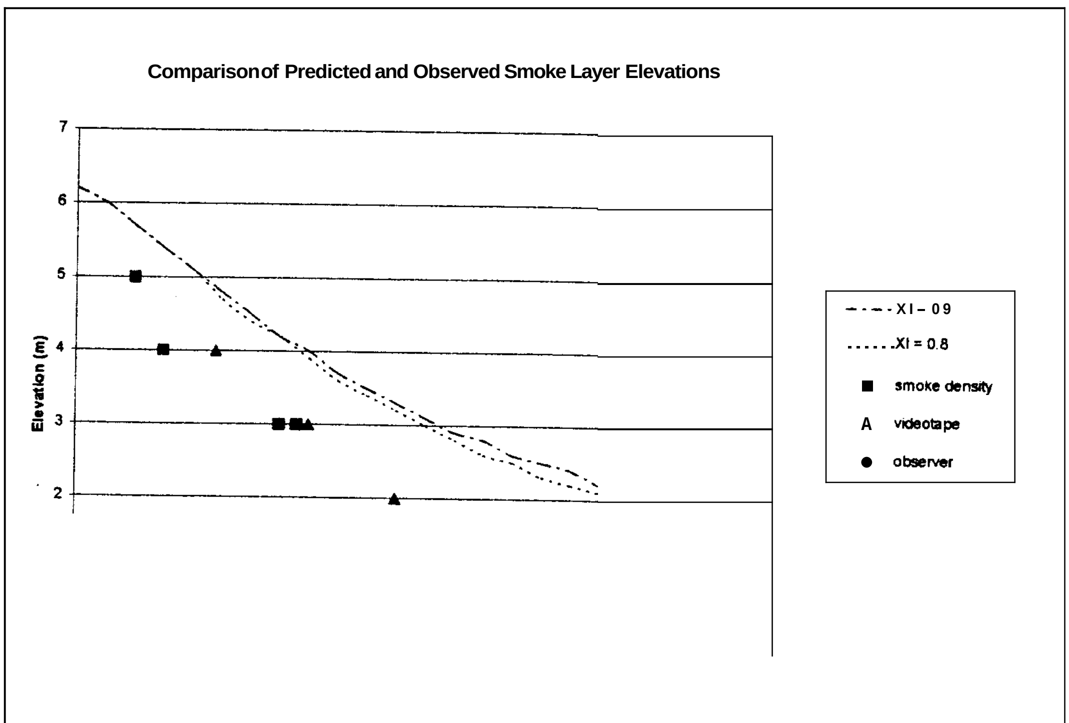


Figure 28 Comparison of Predicted and Observed Smoke Layer Elevations – 6m³

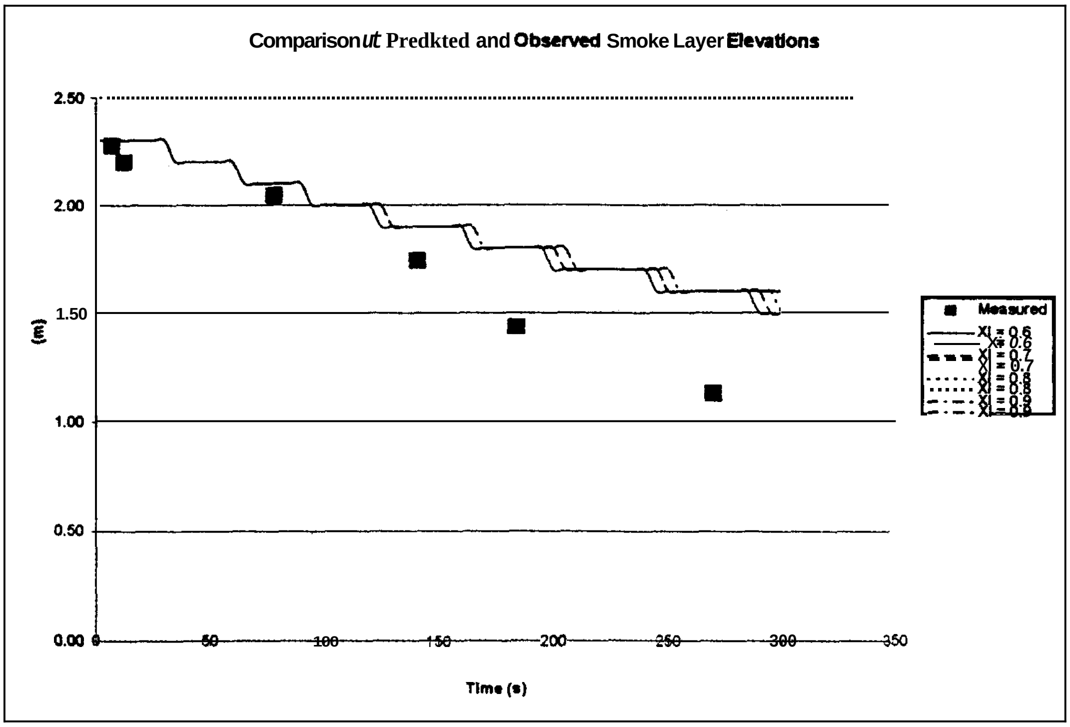
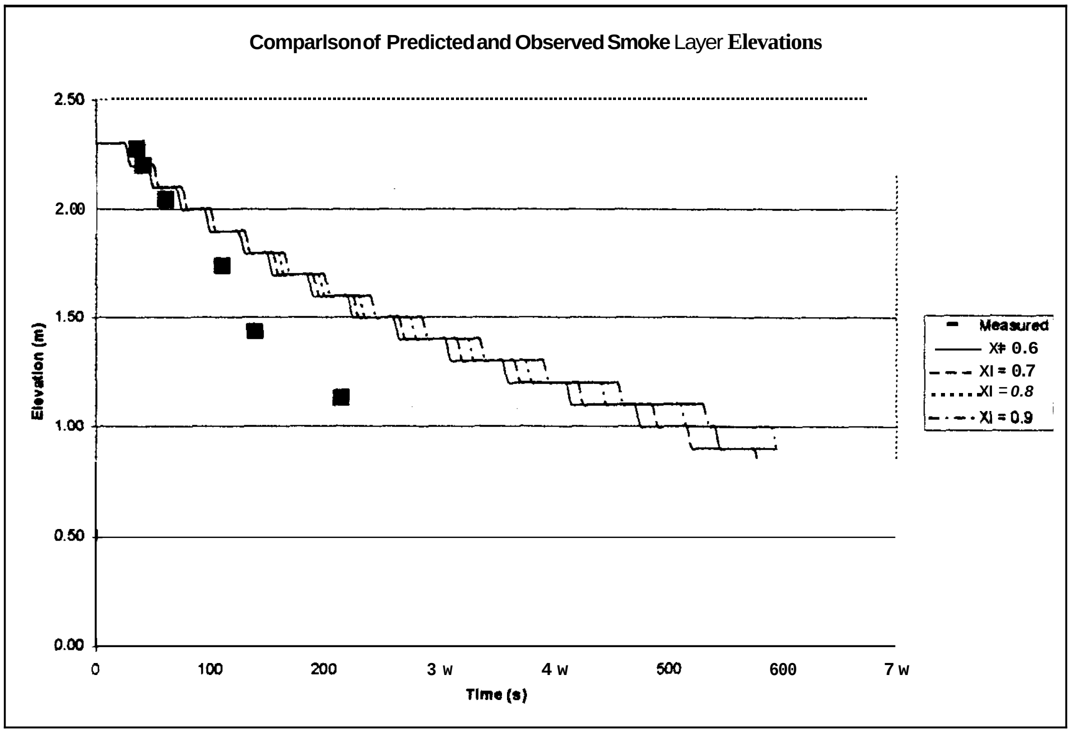


Figure 29 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 28 kW



with Heat Release Rate = 56 kW

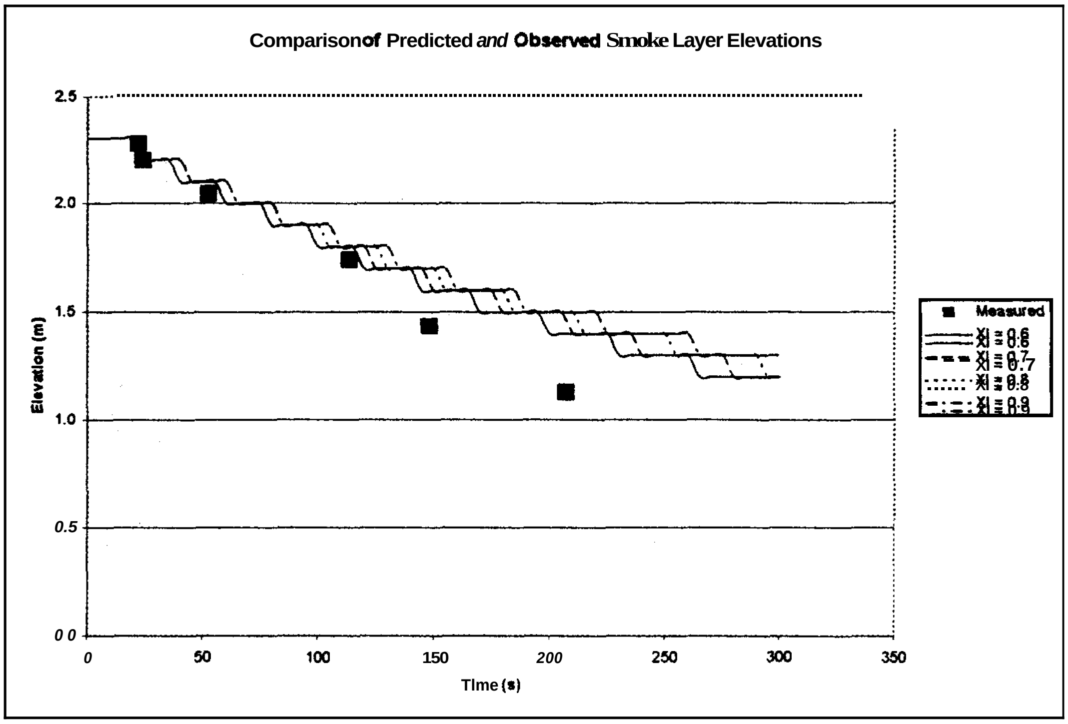


Figure 31 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 112 kW

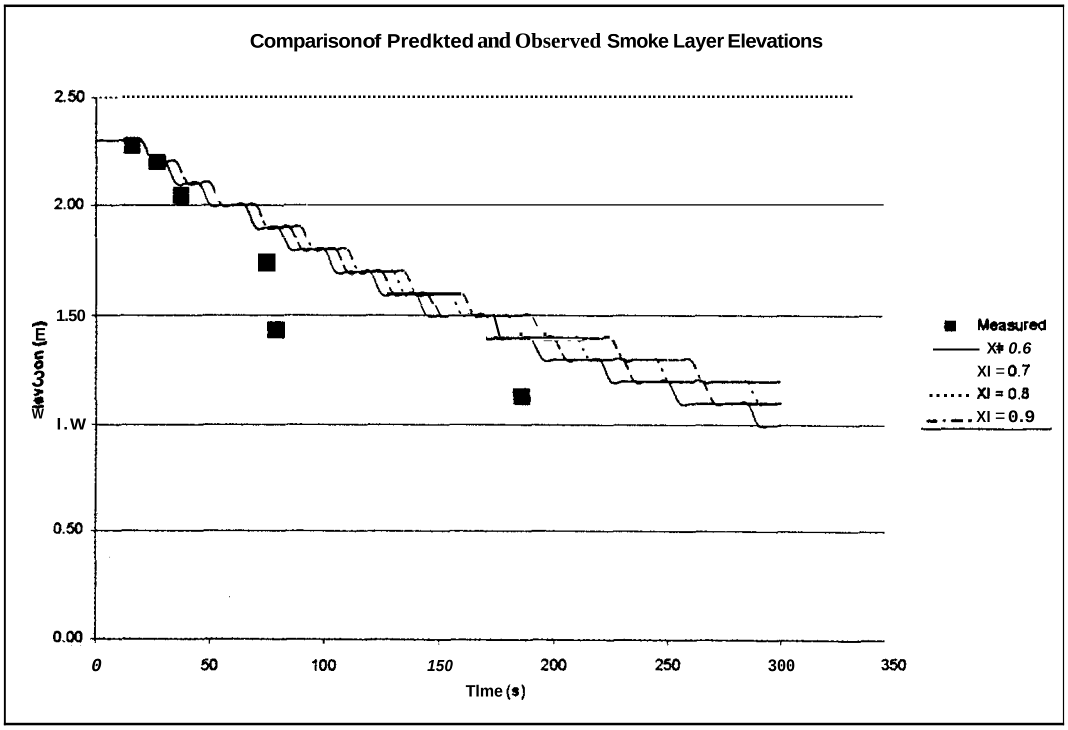


Figure 32 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo

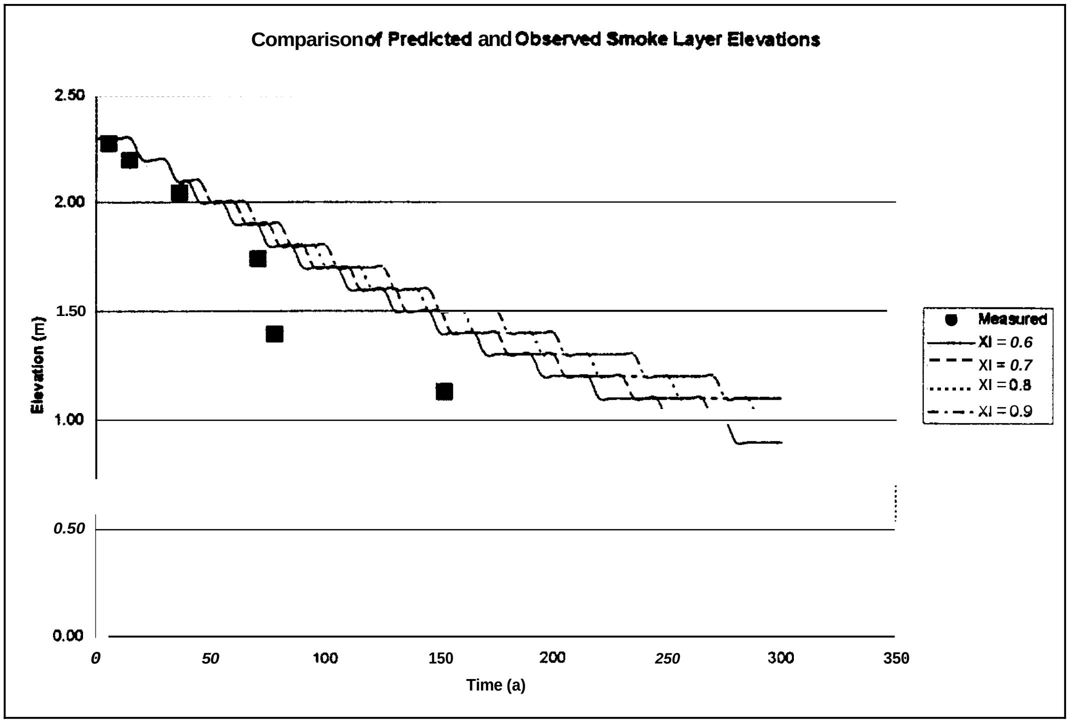


Figure 33 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 224 kW

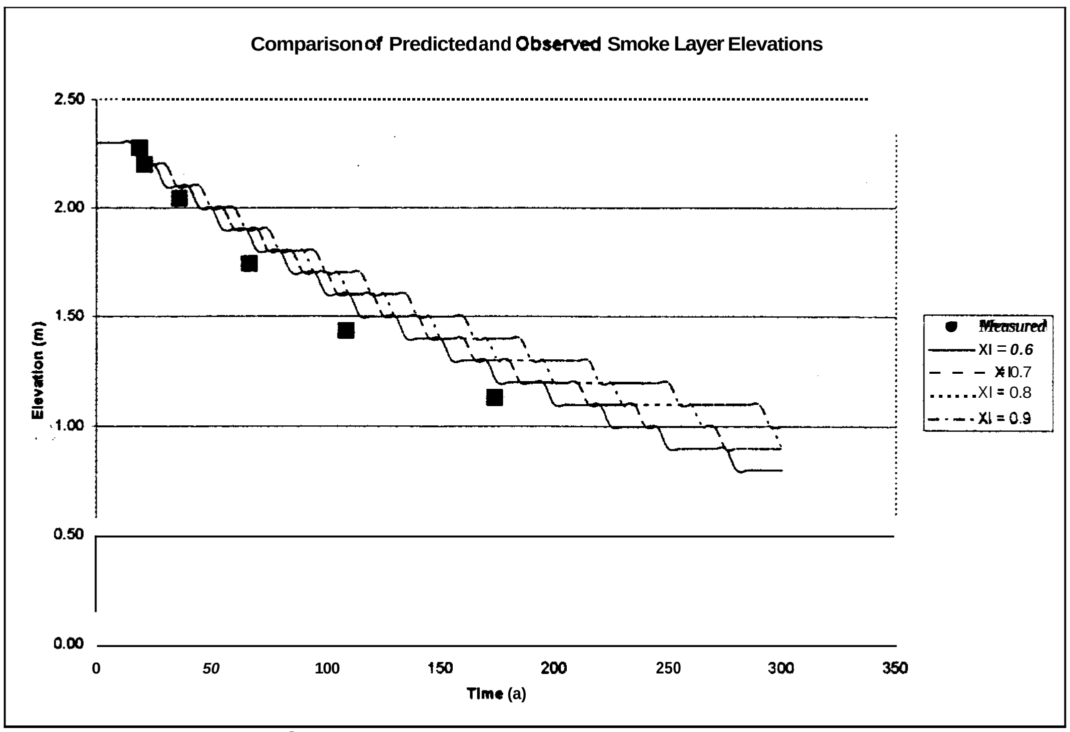


Figure 34 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 280 kW

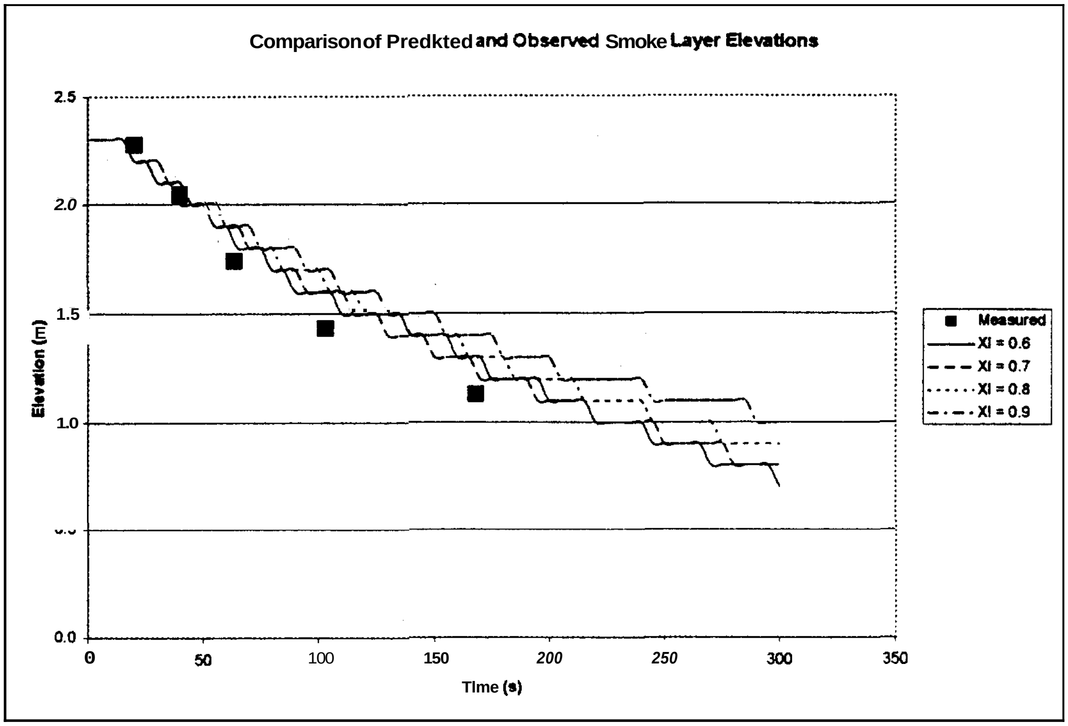


Figure 35 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 336 kW

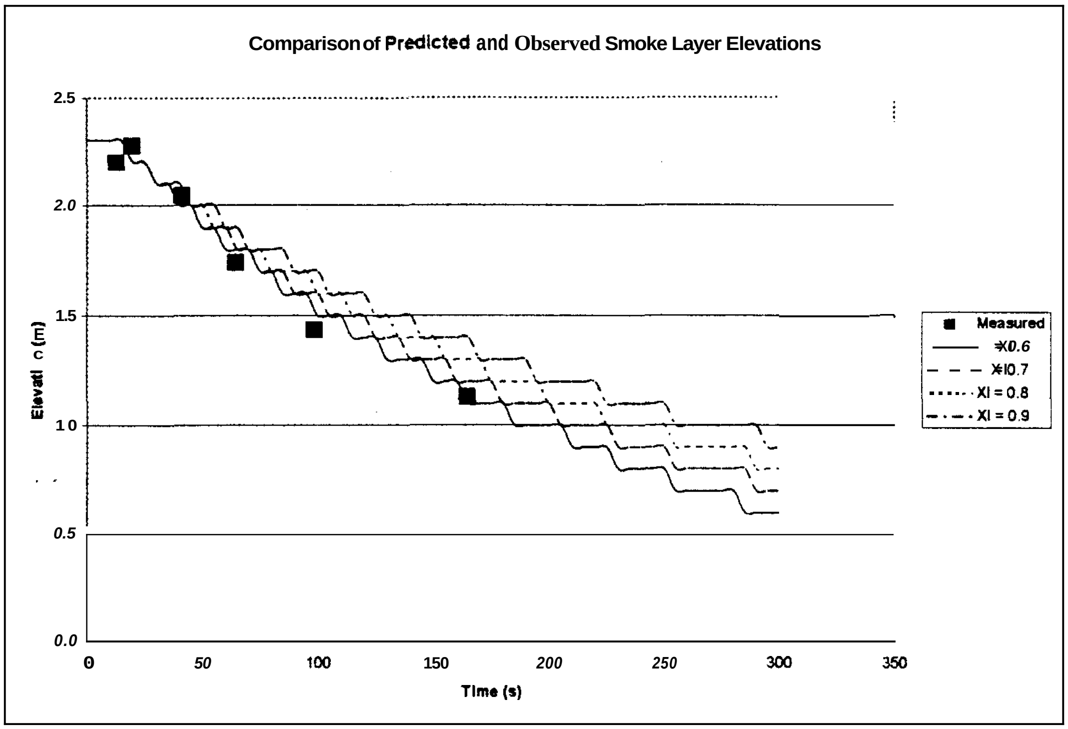


Figure 36 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 392 kW

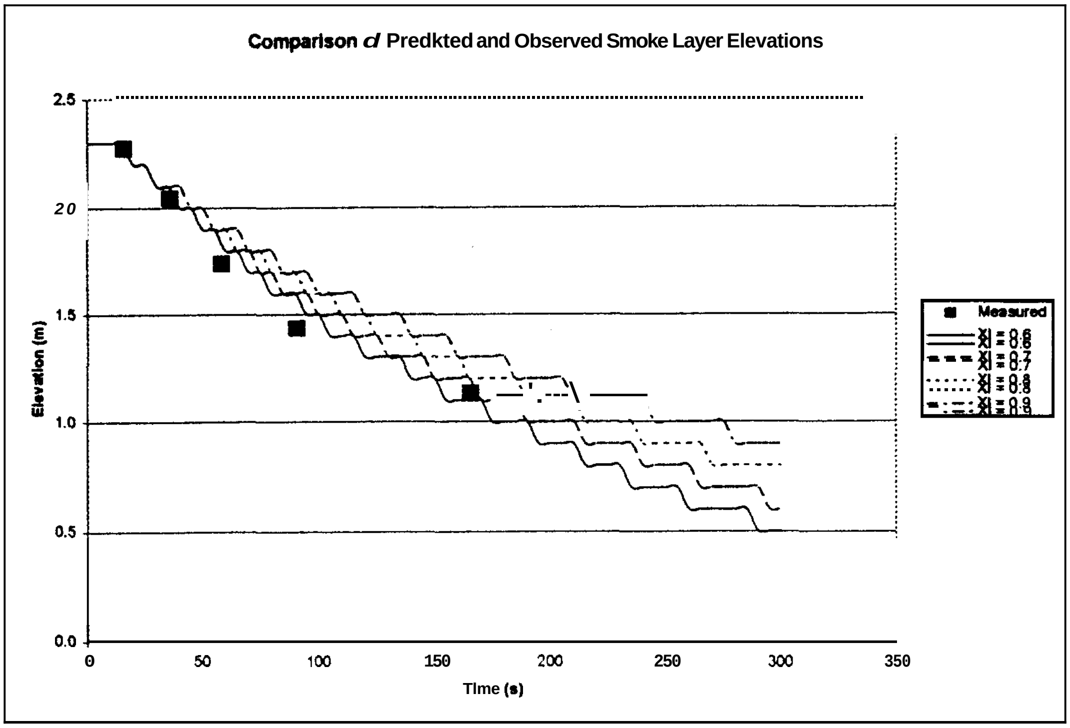


Figure 37 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 448 kW

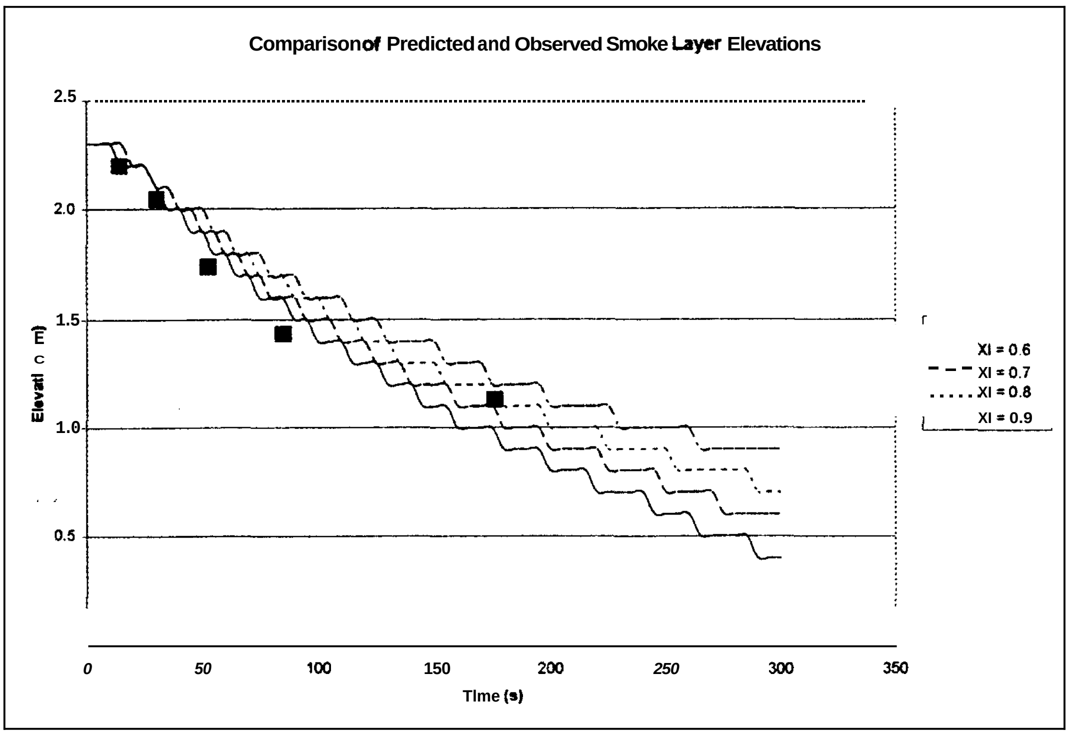


Figure 38 Comparison of Predicted and Observed Smoke Layer Elevations – Nike Silo with Heat Release Rate = 504 kW

DISCUSSION

Smoke Layer Temperature

The documentation for ASET-B[5] notes that lower heat loss fraction values correspond to high aspect ratio spaces with smooth ceilings and fires located remotely from the walls, and that intermediate to higher values should be used in rooms with low aspect ratios, rooms with irregular surfaces, or rooms where the fire is within one ceiling height of a wall. Using this guidance, lower heat loss fiaction values would apply to all of the fire tests in the Nike silo and the fires in the $6m^3$ enclosure that were positioned in the center (tests # 2, **3,** 5, 6 & 7). Intermediate to higher heat loss fractions would be applicable to the tests in the $6m^3$ enclosure where the fire was placed close to a wall or comer (tests **#9,** 12, 13 & 15.) However, ASET-B better predicted smoke layer temperatures in all scenarios when values of the heat loss fraction in the range of 0.7 – 0.8 were used.

In all of the tests, the smoke layer was not a homogeneous temperature, as is assumed by ASET-B. The non-homogeneity of the smoke layer temperature increased with increasing heat release rates. For the purposes of the evaluation of the predictive capability of ASET-B, the average or intermediate thermocouple temperatures are used for comparison with ASET-B predictions.

In many of the tests in the $6m^3$ enclosure, ASET-B overpredicted the smoke layer temperature in the initial portions of the tests. ASET-B assumes an ambient temperature of 21 °C, and the initial temperature of the test enclosure in many of these tests was several degrees below 21 °C. In these cases this was taken into consideration when interpreting the comparison of ASET-B predictions with the test data.

In general, depending on the heat loss fiaction selected, ASET-B provides good predictions of the smoke layer temperature. ASET-B generally provided good predictions of average or intermediate smoke layer temperatures when heat loss fractions in the range of 0.7 – 0.8 was used.

Smoke Layer Elevation

The ASET-B predictions of the smoke layer elevation did not vary significantly with the selection of heat loss fraction. This is to be expected, since according to Charles's Law, gas volume varies proportionately with changes in temperature referenced to 0 K.

In the tests in the $6m^3$ enclosure, ASET-B predicted smoke layer elevations to within one meter (or within approximately **20%** of the floor to ceiling height). In the tests in the Nike silo, ASET-B generally predicted that the smoke layer was at a higher elevation than was measured using the *N%* rule. These differences were within approximately one meter, which represented approximately 40% of the floor to ceiling height of the test enclosure. However, ASET-B predictions better corresponded to the data as the heat release rate increased.

One possible reason that the ASET-B predictions did not better agree with the data from the Nike silo tests with lower heat release rates could be due to uncertainty with the *N%* rule at lower heat release rates. ASET-B temperature predictions agreed well with data in the $6 m^3$ enclosure, even at lower heat release rates. The smoke layer data in the $6 m^3$ enclosure was gathered by direct observation, by visual interpretation of video data, and by smoke density meter. In interpreting the temperature data in the Nike silo tests where the fires had lower heat release rates, whether or not the layer was found to be at a given elevation would typically change fiom "true" to "false" repeatedly. This can be seen in the following data from thermocouples located 76 mm below the ceiling in the 28 kW tests (when the *N%* rule indicated that the smoke layer was present at this elevation, the smoke layer temperature was displayed):

Table 2 – Sample of Data Using the N% Rule for a Thermocouple Located 76 mm Below the Ceiling in Tests in the Nike Silo with Heat Release Rates of 28 kW

Time (s)	Layer Temperature (°C)
0.0	20.8125
1.9	FALSE
3.7	FALSE
5.5	FALSE
7.2	20.95
9.0	20.8625
10.7	20.825
12.5	FALSE
14.3	FALSE
16.1	FALSE
17.8	FALSE
19.6	FALSE
21.4	FALSE
23.2	FALSE
24.9	FALSE
26.7	21
28.4	21.025
30.2	21.2
32.0	21.175
33.8	21.025
35.5	FALSE
37.3	21.1
39.1	FALSE
40.8	FALSE
42.6	21.0625

CONCLUSIONS

For experiments in enclosures that measured *5.62* meters × *5.62* meters × 6.15 meters and 18.9 meters × 9.1 meters with a ceiling height of *2.35* meters with heat release rates ranging fiom 28 kW to **504** kW, ASET-B provided reasonably accurate predictions of smoke layer temperature when a heat loss fractions in the range of 0.7 – 0.8 is used as input.

In these scenarios, ASET-B predictions of the smoke layer elevation were typically accurate to within 1 meter or **15%** of the floor to ceiling height.

As with any empirically based analysis, caution should be exercised when applying these conclusions in scenarios that differ from those that were used to generate the test data, e.g., with higher or lower heat releases, with differing room geometry, or with differing aspect ratios.

ACKNOWLEDGEMENTS

Shirelle Johnson, a student intern, performed most of the ASET-B modeling that was used for comparisons with the test data, and prepared the initial spreadsheets that were used for interpreting the comparisons. The National Institute of Standards and Technology provided financial assistance under grant #60NANB0D0098. Members of the SFPE Task Group on Computer Model Evaluation provided suggestions on how to approach the comparison effort.

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Evaluation of the Computer Fire Model DETACT-QS

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INTRODUCTION

The proper use of engineering design methods requires an understanding of their applicability and limitations, since all design methods are, at least to a certain extent, empirically based. Equations or constants used within design methods are frequently based on curve fits to data from experiments. Typically, the experiments used to develop the correlations were conducted under a limited set of conditions, e.g., compartment sizes, heat release rates or fire growth rates. If the design method is used for an application that falls outside of the bounds of the experiments used to develop the correlations used in the design method, uncertainty may be introduced.

The potential for uncertainty in computer models is greater than within basic closed form equations. Errors can be introduced in the numerical methods used to solve integral or differential equations, or more simply in math errors that were created during coding of the program.

To facilitate the use of engineering design methods and the review of designs developed using engineering methods, the Society of Fire Protection Engineers has summarized and evaluated a number of engineering methods, including several of those which predict radiation from pool fires,[1] predict the effects of thermal radiation to people,[2] and predict ignition of objects when exposed to thermal radiation.[3]

These methods are typically simple algebraic or differential equations. Given the added potential for the introduction of uncertainty, it is also necessary to evaluate computer models. In many cases, existing computer models have been released to the engineering community without sufficient technical guidance for the user to understand the capabilities or limitations of the model. As noted by Howard Emmons in 1991, "there should be a fire model validation group ..." to review computer models that are used to demonstrate public safety.[4]

EVALUATION APPROACH

The Society of Fire Protection Engineers formed a task group in 1995 to evaluate the scope, applicability and limitations of computer models. The Task Group chose DETACT-QS,[5] a model for predicting thermal detector response, as the first model to undergo evaluation. DETACT-QS was selected since it is a relatively simple model and it is widely used within the fire protection engineering community. The resulting evaluation document is intended to supplement the model's original documentation by demonstrating the capabilities and limitations

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of the model and by highlighting underlying assumptions that are important for users to consider when applying the model.

After examining several approaches to evaluating a computer model, the **Task Group** decided to follow the ASTM ***Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models,*** E-1355.[6] The ASTM guide "provides a methodology for evaluating the predictive capabilities **of** a fire model for a specific use." Specifically the method addresses four areas of evaluation: **1)** model definition and evaluation scenarios, **2)** verification of theoretical basis and assumptions used in the model, **3)** verification of the mathematical and numerical robustness of the model, and 4) quantification of the uncertainty and accuracy of the model predictions.

This paper summarizes the results of SFPE's evaluation of DETACT-QS.

EVALUATION REPORT

The DETACT-QS evaluation report consists of eleven sections:

- Introduction
- Model Description
- Evaluation Scenarios
- Theoretical Basis **for** Model
- Mathematical Robustness
- Model Sensitivity
- Model Inputs
- Model Evaluation
- Quantifying Model Evaluation
- Summary of Analysis
- List of Limitations/Guidelines

Introduction

While the purpose of the evaluation is to provide information on the technical features, theoretical basis, assumptions, limitations, sensitivities, and guidance on the use of DETACT-QS, the evaluation is intended for use only by persons competent in the field of fire safety and is intended only to supplement the informed judgement of qualified users.

The evaluation is based on comparing predictions from DETACT-QS with results from full-scale fire experiments conducted in compartments with ceiling heights ranging from **2.44** m to 12.2 m and peak fire heat release rates ranging from 150 kW to 3.8 MW. The use of DETACT-QS with building geometries or fire characteristics other than those used in this evaluation may require further evaluation or testing.

Model Description

DETACT-QS is an empirical model, which *is* based on data correlations from a series of **large**-scale fire experiments. The model solves a definite integral using a quasi steady slate assumption. It then solves several algebraic equations to produce predictions. DETACT-QS is composed of an algorithm which predicts the maximum temperature and velocity of an unconfined ceiling jet, under a smooth, flat, horizontal ceiling at a given radius from the centerline of the fire. It also utilizes a lumped mass, convection heat transfer algorithm for predicting the activation time of a thermal detector.

Several assumptions are implicit within DETACT-QS. The model assumes that the detector being analyzed is mounted on an unconfined, unobstructed, smooth, flat, horizontal ceiling and that the detector is located at the points of maximum temperature and velocity within the ceiling jet. Only convective heat transfer is considered between the ceiling jet and the thermal detector; no conductive loss or radiative heat transfer is considered. The detector is treated as a lumped mass. Temperatures and velocities of the plume and ceiling jet are uniform and assumed to be the maximum values in the plume. The fuel package and the plume are assumed to be in an unobstructed vertical axis. No ventilation or stratification effects are considered. No transport time (or lag time) is considered for the hot gases to travel from fuel to the detector. For each heat release rate input interval, the heat release rate is averaged over the interval and assumed constant.

Several parameters are required as input into DETACT-QS: the height of the ceiling above the fuel, the distance of the detector from the axis of the fire, the initial room temperature, the detector actuation temperature, the detector response time index, and the total heat release rate as a function of time for a given fire. The heat release rate is input in time-heat release rate pairs. The model predicts gas temperature of the ceiling jet and detector temperature at user specified time intervals and the detector actuation time.

Evaluation Scenarios

The evaluation scenarios represent compartment configurations ranging from residential scale rooms up to larger compartments typical of those found in commercial and industrial settings. The scenarios are limited by the test data available for comparison with model predictions. Test data fiom Underwriters' Laboratories, Factory Mutual, and the National Institute of Standards and Technology was used for the evaluation. These scenarios involve ceiling heights ranging from 2.44 m to 12.2 m, horizontal dimensions ranging from 5.5 m × 9.2 m to 61 m × 76 m, and peak fire heat release rates ranging from 150 kW to 3.8 MW.

Based on the model assumption of an unconfined ceiling, the small compartment scenarios (i.e., with horizontal dimensions of 5.5 m × 9.2 m) may not be appropriate for use with DETACT-QS. These scenarios were chosen to examine the capabilities or limitations of DETACT-QS under confined ceiling conditions.

Theoretical Basis for the Model

DETACT-QS uses an assumption of quasi-steady gas flow temperatures and velocities to evaluate detector response to a user defined fire. "With this assumption, correlations for ceiling-jet temperatures and velocities obtained from experiments using steady fire energy release rate Sources can be used to evaluate growing fires. The growing fire is represented in the calculation as a series of steady fires with energy release rates changing in time to correspond to the fire of interest."[5] The correlations used in DETACT-QS were developed by Alpert[7] and use a response time index developed by Heskestad.[8]

Performing an energy balance on the detector results in the following equation:

$$\frac{dT_{link}}{dt} = \frac{\sqrt{U_g}\left(T_g - T_{link}\right)}{RTI}$$

Where T_{link} is the detector temperature, T_g and U_g are the ceiling jet temperature and velocity, and RTI is the detector's response time index. **A** complete derivation of this equation is available in the evaluation report. DETACT-QS uses the Euler method with a one second time step to solve this differential equation to predict the detector temperature as a function of time. When the detector temperature is less than or equal to the activation temperature, the time is incremented by one time step, the intermediate results are printed, and the process is repeated. When the detector temperature exceeds the activation temperature, the calculation is completed

Mathematical Robustness

The mathematical robustness of the model was examined by recreating the model with another mathematical solver. The predictions of the model and the recreation are then compared for level of agreement.

This analysis revealed two minor inconsistencies. Although the program calculates **gas** and detector temperatures consistent with those expected, the program prints the previous gas and detector temperature at the printed time interval. Thus, the intermediate detector and gas temperature values printed are those from the previous second (i.e., the detector and gas temperatures displayed at 10 seconds will be values calculated for **9** seconds).

The second inconsistency is that the subroutine calculating detector temperatures adds one second after the calculations are performed. This one-second addition results in printing final detector activation times one second greater than activation times expected.

Model Sensitivity

A sensitivity analysis was used to evaluate the relative magnitude of change that can be expected by changing an input parameter. Some input parameter changes result in small or insignificant changes in model predictions while others may result in large changes in the predicted values. Identifying the input parameters to which the model is most sensitive is important information to the user.

The results of the sensitivity analysis identify **the** input parameters that have the greatest effect on, or change in, the output variables. **A** nominal value for each input parameter is chosen to establish a base case. The input parameters are then individually varied over a finite range. If the relative change in the output variable of interest is greater than the change in an input parameter, the model **is** more sensitive to that parameter. If the output variable changes very little with a relatively large change in the input parameter, the model is less sensitive to that parameter.

The results of the sensitivity study are presented in terms of a sensitivity ratio. This ratio is the percentage change in the predicted actuation time over the percentage change in the input parameter of interest. This ratio can be expressed as

$$\frac{\%\ \text{Change in } t_{act}}{\%\ \text{Change in } X}$$

If this ratio is greater than one (1.0) then the actuation time is more sensitive to that parameter. This is to say that, e.g., a ten percent increase in the input parameter results in a greater than ten percent increase (or decrease) in the predicted output.

For DETACT-QS, in general, changing a single input parameter results in a change in the resulting actuation time (output) of less **than** the percentage change in the input parameter. That is, in most cases when an input parameter is varied by ten percent (10%) the time to actuation will vary by less than ten percent (<10%). Two exceptions are the input parameters detector actuation temperature and, when a slow t-squared fire is used, fire growth rate. For the former, the results of many sensitivity analyses yielded a change in predicted actuation time vs. change in input actuation temperature ratio greater than one. The larger change in output in comparison to the change in actuation temperature indicates that the model is more sensitive to the actuation temperature than it is to other input values. This condition underscores the user's need for care and understanding with regards to uncertainties relative to the thermal detector device being modeled and any environmental conditions that may affect the activation of that device.

In the case of a slow t-squared fire, the predicted actuation time will greatly increase due to the relatively slow development of the fire. This increase in predicted activation time emphasizes the need for the designer to consider appropriate safety factors that apply to the entire fire scenario under examination, not a single safety factor used for all scenarios "as-a-rule". Very small source fires, especially smoldering, fall outside the bounds of this analysis and are unlikely to be accurately predicted, either for ceiling jet temperatures or detector actuation, by DETACT-QS.

Figure 1 shows a typical range of sensitivity of output to variations in input parameters.

Evaluation Scenario Model Inputs

Three sets of experimental data were used in this evaluation. This section describes the test conditions, including geometry and construction of the compartment, location and heat release rate history of the fire, location and characterization of the thermal detector, and locations and descriptions of measurement instrumentation used in the test. From this information, the inputs to the model are developed.

The first set of tests **was** conducted under a **30** m by 30 meter adjustable height ceiling. The ceiling had horizontal dimensions that were smaller than those in the test facility, and exhaust was provided above the ceiling, which allowed for large fire tests to be conducted without the formation of a smoke layer below the ceiling. The second set was conducted in a room 5.6 by 9.2 m with a ceiling height of **2.4** m. The third set was conducted in a facility with a ceiling height of 8.8 m and horizontal dimensions of **61** m by 76 m.

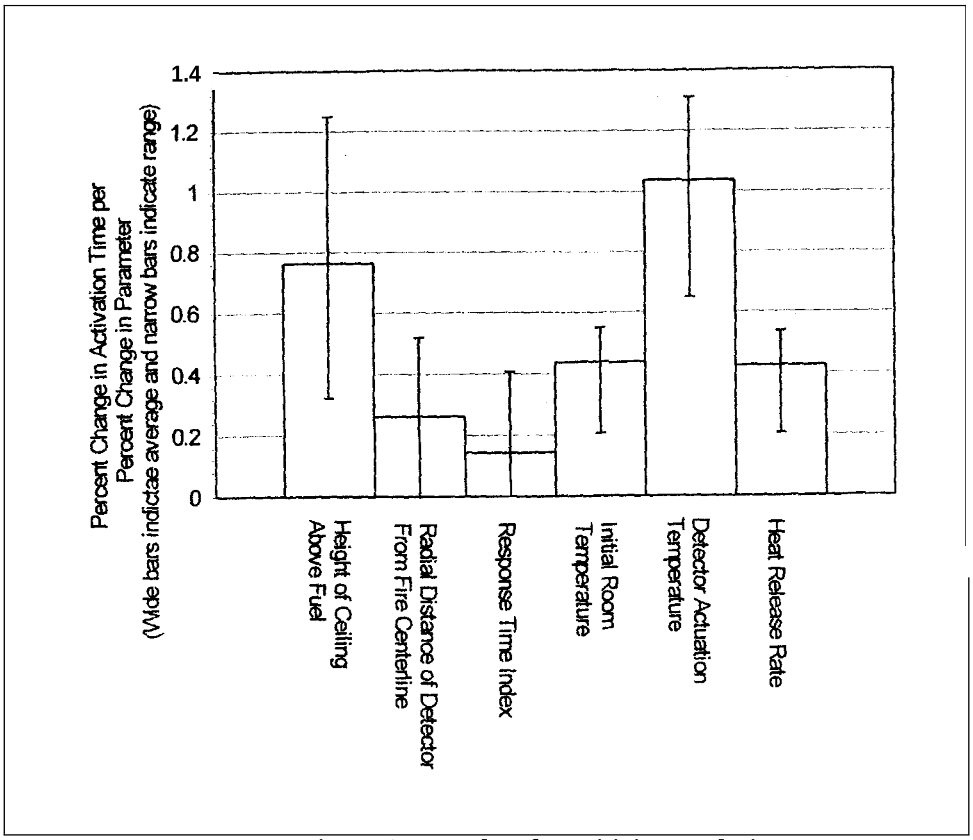

Figure 1 – Results of Sensitivity Analysis

In the first set of tests, tests were conducted with the ceiling positioned at heights **of** 3.1, 4.6, 6.1, 7.6, 10.7, and **12.2** m. The fire source in these tests consisted of a heptane burner constructed from **a** nominal 12 mm pipe manifold. The heat release rate of the test fires followed the following relationship:

Time (s)	**Heat Release Rate (kW)**
0 through 40	$\dot{q} = 0.1875(t + 10)^2$
Time > 40	$\dot{q} = 0.0117(t + 160)^2$

Brass disk thermocouples with **known** RTI's were used to estimate the response of thermal elements in the ceiling jet. The disk thermocouples were constructed with chromel-alumel thermocouple wire fastened to brass **disks** of various thicknesses. The three types of disk thermocouples **were** identified as slow, medium, and fast. The RTI's of the thermocouples were measured in the sprinkler plunge oven in general accordance with UL1767. The RTI's of the **disk** thermocouple were measured perpendicular to and aligned to the flow and a variation in the RTI of less than 10% was measured. The RTI's of the disk thermocouples are given below.

*Type	Thickness (mm)	RTI ($m^{½}s^{½}$)
Slow	**6.54**	**287**
'Medium	**3.18**	**164**
Fast	0.41	**32**

The second set of tests modeled was conducted in a room *5.6* by **9.2 m** with **a** ceiling height of **2.4** m. The walls and ceiling were constructed of a wood frame covered with **12.7** mm gypsum board. The floor was concrete. **A** hollow steel door **2.1** m high by 0.91 m wide **was** closed for all experiments. The air gap under the door measured **25** mm. The ceiling vent consisted of an open stairway, which measured **2.7** by 0.9 **m** leading to an upper floor which gave the experimental setup the effect of a basement in a residential occupancy.

The fire source in this experimental series consisted of a methane gas burner with piloted ignition. **A** computer was programmed to control the flow of methane gas through four mass flow controllers arranged in parallel. Three fire sizes were used that grew in proportion to time squared: a fire that reached 1055 kW in **150** seconds (a = 0.0468 kW/s^2), a fire that reached 1055 kW in **300** seconds (a = 0.01 17 kW/s^2), and fire that reached 1055 kW in **600** seconds (a = 0.0029 kW/s^2). In addition to varying the heat release rate of the fire, the burner was placed in various locations within the room; away from any wall (detached experiment), against a wall (wall experiment), and in a comer (comer experiment).

Instrumentation consisted of four vertical arrays of twelve type K, 0.51 mm bare bead thermocouples. In each array thermocouples were located **0, 25, 50, 75,** 100, **125, 150,250,350, 450, 550,** and 900 mm below the ceiling. **A** quick response residential pendant spray sprinkler was installed on the ceiling at each of the four locations in accordance with **NFPA 13D, *Sprinkler Systems in One and Two Family Dwellings and Manufactured Homes.*** The sprinklers used in the experiments were commercially available residential pendant spray sprinklers. The sprinklers had an activation temperature of 68 "C and a RTI of **55** $(m\text{-}s)^{½}$.

The third test series was part of a sequence of fire tests which used wood cribs, cotton fabric, polyurethane and polyvinyl chloride **as** tests fuels. Smoldering and flaming fire tests were conducted. The initial room temperature was approximately **25** "C. The elevation of the ceiling above the fuel was varied by raising the elevation of the fuel above the floor. However, it was found that raising the load cell resulted in difficulties in maintaining a level platform, and the results were deemed unreliable. Of the remaining tests, only two were used, because they alone resulted in temperatures that were sufficiently high to activate heat detectors and because they showed consistency in mass loss measurements.

Heat detectors with a nominal actuation temperature of **57.2 °C** were located approximately 100 mm below the ceiling at radial distances of **3.05**, **6.1** and **12.2** meters from the crib centerline. These heat detectors were later determined to have an activation temperature of 60 °C and a time constant of **26** seconds at a reference of **1.5** meters per second, which corresponds to an RTI of **32.1** $(m\text{-}s)^{½}$.

The heat of combustion for sugar pine was reported as 20,900 kJ/kg in the test report; however, this was later revised by the authors to 12,500 kJ/kg. The mass loss measurements were converted to heat release rates by determining the difference in mass over measurement intervals and dividing by the length of the measurement interval, and multiplying by the calorific value of 12,500 kJ/kg. The heat release rates in the tests ranged from *0* to over **3** MW.

Model Evaluation

The model evaluation compared predictions ***to*** full-scale test data. **ASTM** E-1355 identifies **two** methods of comparing model predictions with full-scale data: "blind calculations" and "Specified calculations." In blind calculations, the specific inputs are not completely defined to the modelers. In addition to comparing the model results in actual end-use conditions, blind calculations can point out misunderstandings in the use of the model. For specified calculations, the model user is provided with the most complete set of input values available, which allows a "best case" comparison of the physics **and** capabilities of the model. Specified calculations were used for the evaluation of DETACT-QS.

The figures below show comparisons of predicted ceiling jet temperatures with measured values.

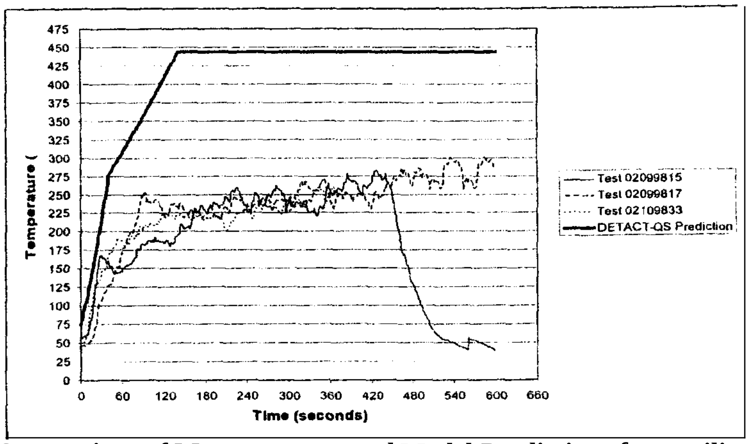

Figure 2 – Comparison of Measurements and Model Predictions for a ceiling height of 3 meters at the Plume Centerline (RTI – 0)

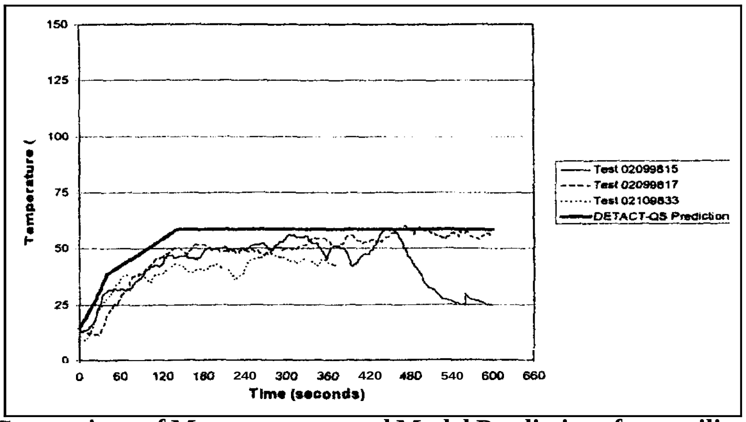

Figure 3 – Comparison of Measurements and Model Predictions for a ceiling height of 3 meters and a Radial Distance of 10 meters (RTI = 0)

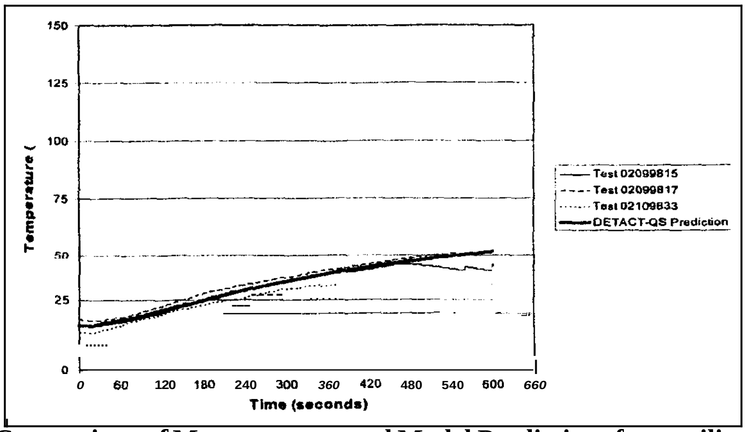

Figure 4 – Comparison of Measurements and Model Predictions for a ceiling height of 3 meters and a Radial Distance of 10 meters (RTI = 287 $m^{½}s^{½}$)

Figures 2 and **3** show a comparison of model predictions and data measurements from the first of tests for a ceiling height of **3** m with a bare thermocouple (RTI = 0) at the plume centerline and at a radial distance of 10 meters. These graphs show that DETACT-QS underpredicts temperatures in scenarios involving **low** ceilings when the detector is close to the fire centerline, but temperature predictions improve **as** the radial distance from the fire to the detector increases. When the ceiling jet temperatures are underpredicted, **DETACT** would predict longer detector activation times than would actually occur. However, as can be seen in figure 4, predictions also improve as the detector RTI increases.

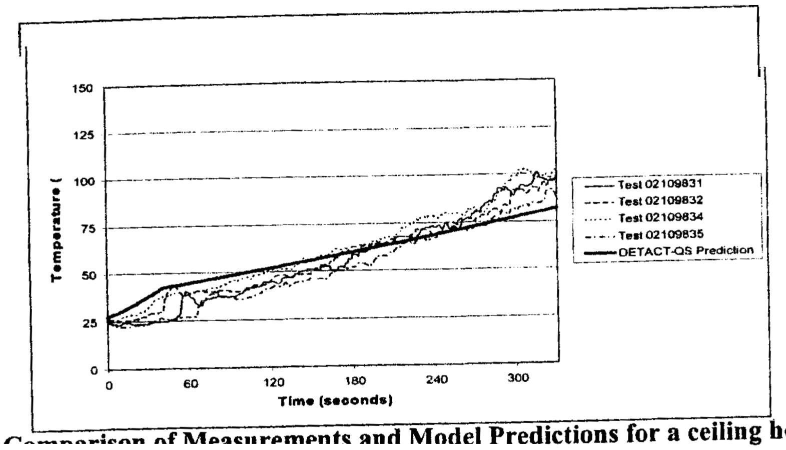

Figure 5 Comparison of Measurements and Model Predictions for a ceiling height of 1
meters at the plume centerline (RTI ~ 0)

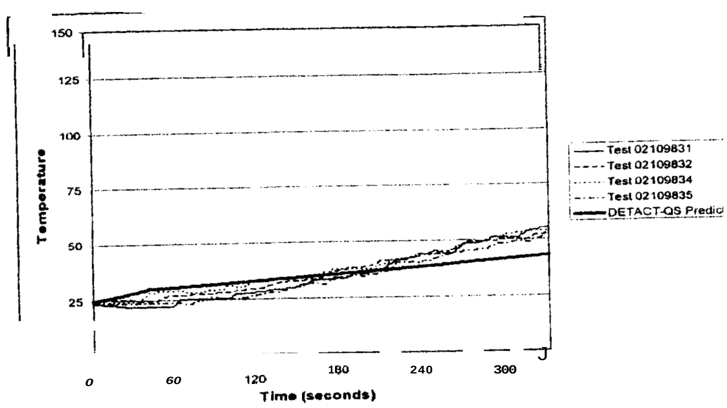

Figure 6 – Comparison of Measurements and Model Predictions for a ceiling height of 12.2 meters at a Radial Distance of 10 meters (RTI ~ 0)

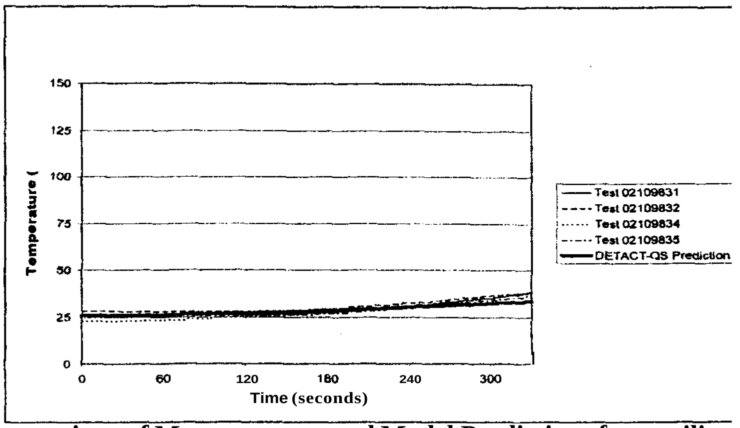

Figure 7 – Comparison of Measurements and Model Predictions for a ceiling height of 12.2 meters at a Radial Distance of 10 meters (RTI = 287 $m^{½}s^{½}$)

Figures **5** – 7 show comparisons of model predictions with experimental data from the first test series with ceiling heights of **12.2** meters. These graphs show that predictions improve as the ceiling height increases. **Also,** the improvement in predictions as response time index increases can **be** seen in figure **7.**

Table **1** shows the results of a comparison of observed detector activation times with predictions in a residential scenario. For the wall fires and comer fires, "HRR" indicates that the actual heat release rate was input into DETACT-QS, and HRRX2 and HRRX4 indicate that the heat release rate was multiplied by **2** or four, respectively when input into the model. As can be seen, DETACT-QS underpredicts ceiling jet temperatures in this scenario, and would therefore predict greater detector activation times than would be expected. This results from the formation of a layer in the room, which would result in the *entrainment* of hotter gasses into the fire plume than DETACT would predict with its assumption of an unconfined ceiling.

Scenario	**Experimental Ceiling Jet Temperature (°C) Average (Range)**	**DETACT – QS Predicted Ceiling Jet Temperature (°C)**		**Difference between the Average Ceiling Jet Temperature and the DETACT-QS Prediction**	
Fire in center of room	**104 (93 – 118)**	**49**		112%	
	107 (102 – 111)	61		*15%*	
	114 (108 – 118)	74		35%	
		HRR	**HRRX2**	**HRR**	**HRRX2**
Fire attached to wall	**100 (99 – 100)**	49	68	51%	32%
	109 (106 – 114)	55	76	50%	30%
	123 (114– 138)	68	96	45%	22%
		HRR	**HRRX4**	**HRR**	**HRRX4**
Fire in comer	113 (109– 118)	46	80	59%	30%
	125 (116 – 137)	49	88	60%	30%
	132 (121 – 143)	68	130	48%	2%

Based on the comparison of predictions with measured values:

- As the ceiling height increased from 3.0 m to 12.2 m, the agreement between the predictions and the data improved.
- There was better agreement between predictions and experimental results for devices with higher RTIs than with devices with lower RTIs.
- Situations where the limitations/assumptions of DETACT-QS cannot be met require further analysis, since the model alone cannot be used with any reasonable expectation of reliability. For example, the use of DETACT-QS would not be appropriate in small areas where a gas layer would develop prior to activation.

Summary of the Analysis and List of Limitations and Guidelines

The last two sections of the evaluation report summarize the results of the evaluation and provide guidelines for use of the model. This section of the evaluation is targeted at a wide audience to include qualified users as well as non-users who may need to evaluate building designs based on the output of the model. In addition, a list of references to all the documents relevant to the evaluation will be included in this section.

ACKNOWLEDGEMENTS

The contributions of the volunteer members of the SFPE Computer Model Evaluation Task Group, without whom the progress summarized in this paper would not have been possible, is greatly appreciated. Special thanks is also due to the National Fire Protection Association, the National Institute of Standards and Technology, and the membership of the Society of Fire Protection Engineers, whose financial support was instrumental to the success of these activities.

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